Hotter, Denser, Faster, Smaller... and Nearly-Perfect: What's the Matter at RHIC?

BROOKHAVEN NATIONAL LABORATORY

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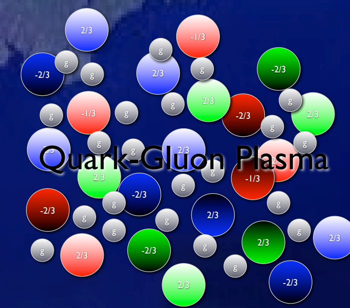
World Year of
PHYSICS
2005
www.physics2005.org

In a <u>single year</u>,
1905,
Einstein published four papers, three of which could have won a Nobel Prize (and one did!)

The importance of Einstein's 1905 papers has been felt since throughout all of modern physics... from the largest to the smallest scales

A Brief Roadmap

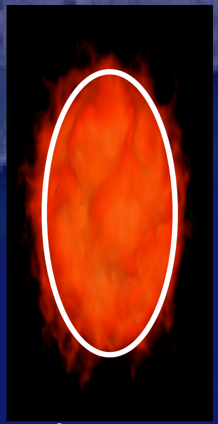
1. The Femtoworld



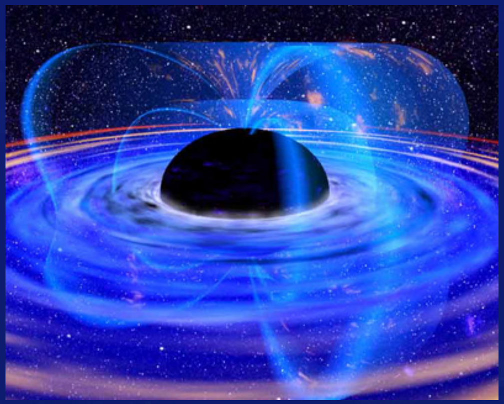
2. Quarks, Gluons, States of Matter

3. What we do at RHIC

4. Counting with PHOBOS

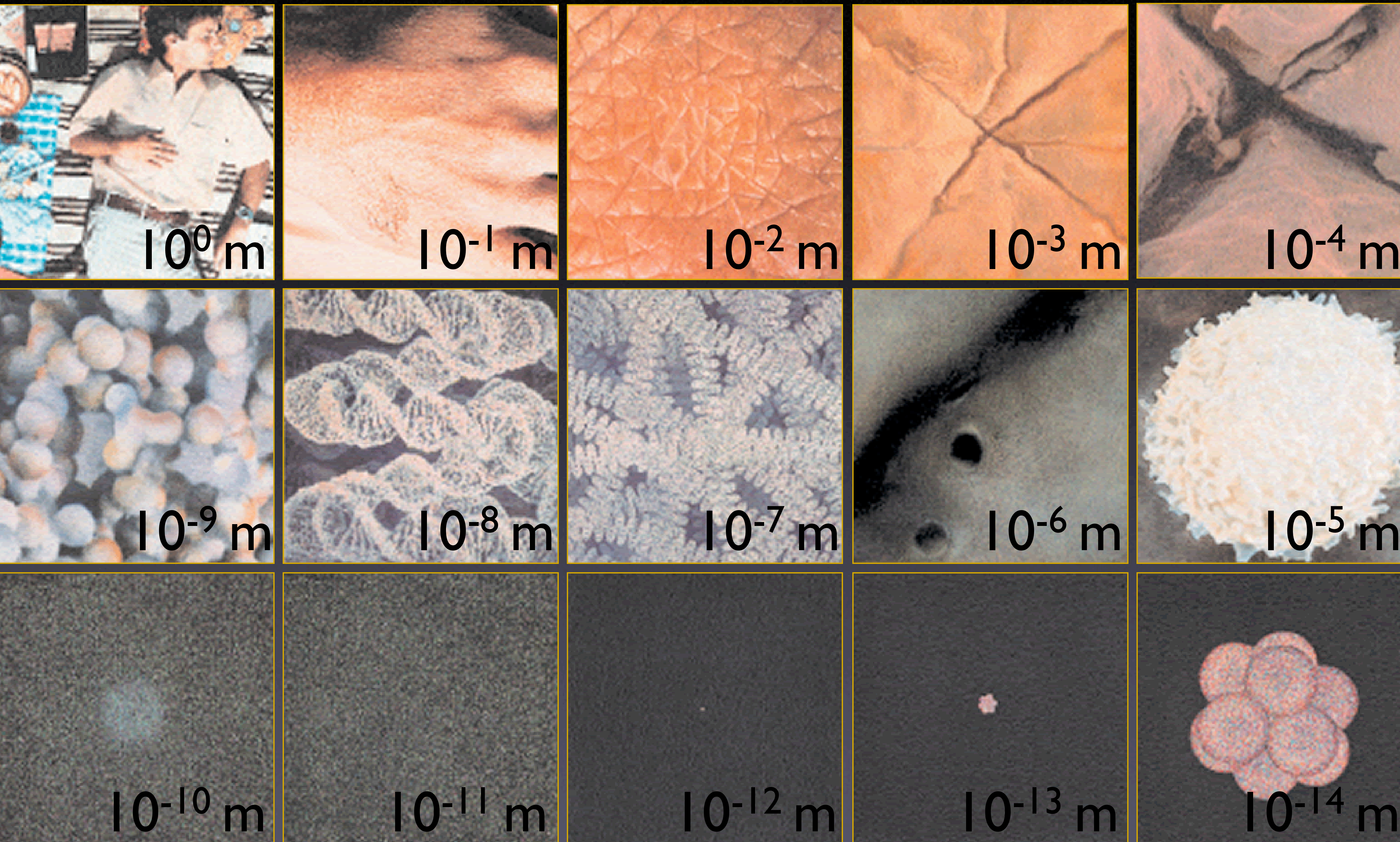


5. Creating matter at RHIC



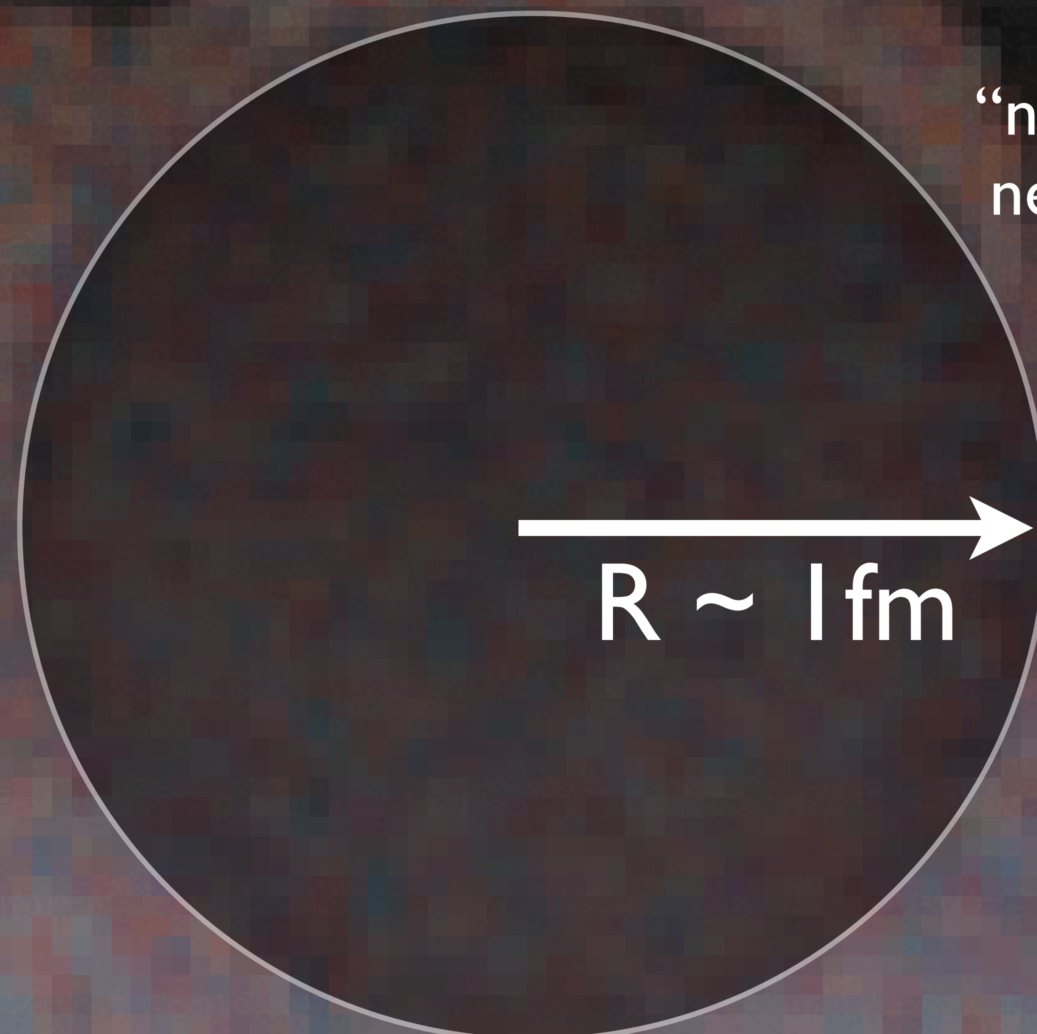
6. The Future

Powers of 10


10^{0} m
10^{-1} m
10^{-2} m
10^{-3} m
10^{-4} m
10^{-9} m
10^{-8} m
10^{-7} m
10^{-6} m
10^{-5} m
10^{-10} m
10^{-11} m
10^{-12} m
10^{-13} m
10^{-14} m

“The Femtoworld”

“nucleon” =
neutron or
proton

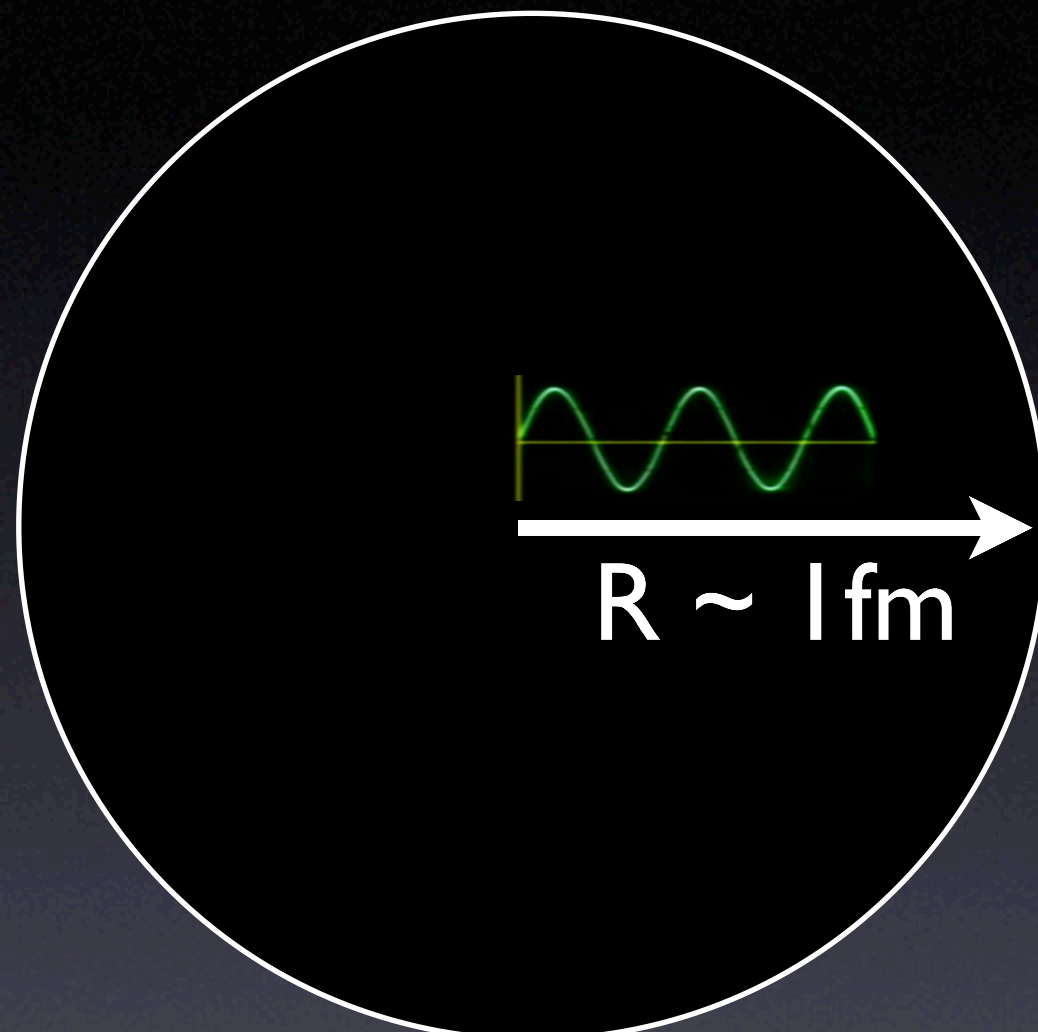


In 2005, “Nuclear Physics” is the study of the Particles and Forces active at the “femtometer” scale

1 femtometer = 1fm = 0.000000000000001m

Adopted in <u>1964</u>, it comes from the <u>Danish</u> or <u>Norwegian</u> *femten*, meaning *fifteen*.

Time in the Femtoworld

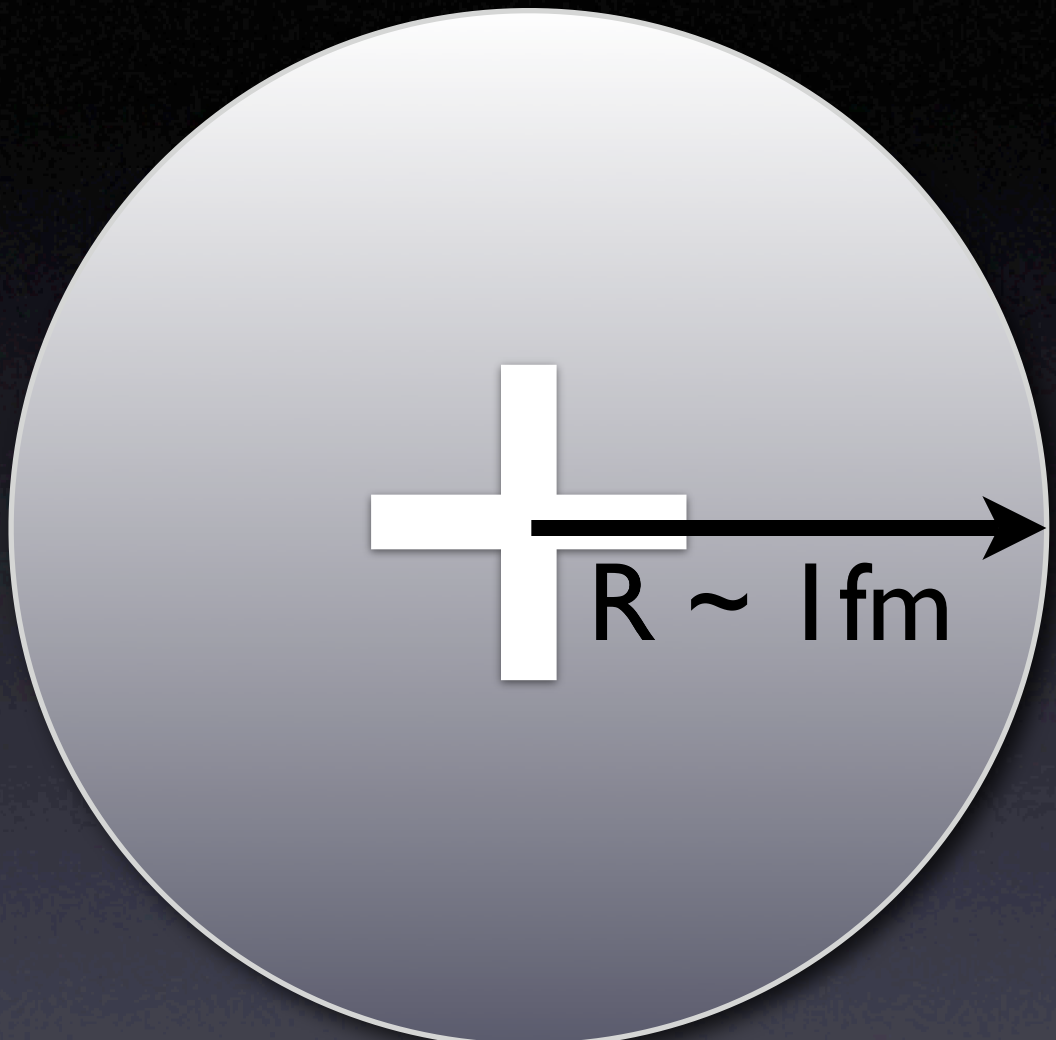


It takes light $3x10^{-24}$ seconds (3 “yoctoseconds”) to travel 1 femtometer in vacuum.

1 ys = 0.000000000000000000000001 sec

This is the basic “time scale” of “strong interaction” physics

What’s in a proton?



We have long known that a proton has a charge, mass, size and spin, but none of these properties point to what’s “inside”

The Particle "Zoo"

1890 1900 1910 1920 1930 1940 1950 1960 1970

e^- p n e^+ $\mu^\pm$ $\pi^\pm$ $K^\pm$ π^0 $\Sigma^\pm$ $\bar{p}$ $\bar{\Lambda}^0$ ρ

K^0 Ξ^- ν_e Ξ^0 ω

η

Λ^0 $\bar{n}$ K^*

Δ Σ^0 ν_μ

ϕ

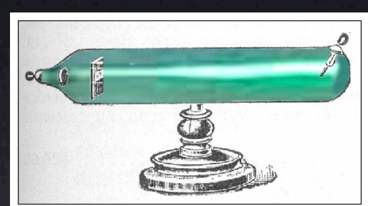
f

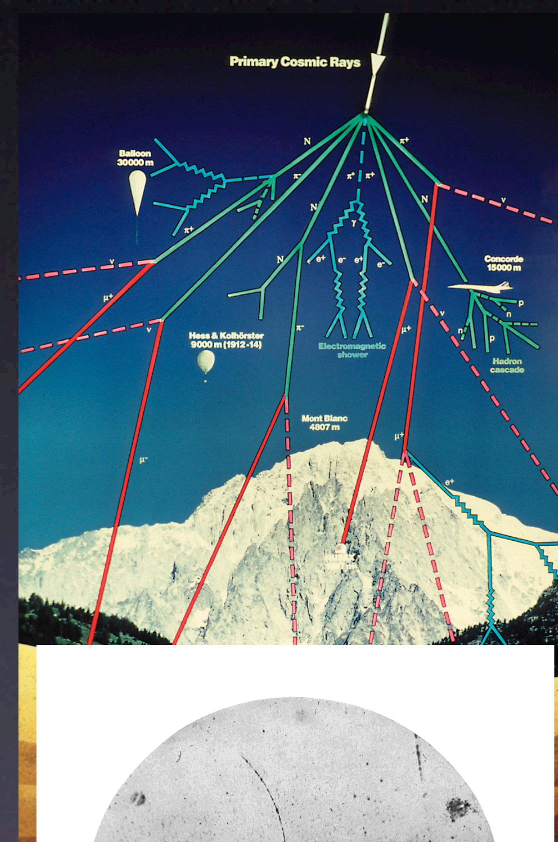
a_2

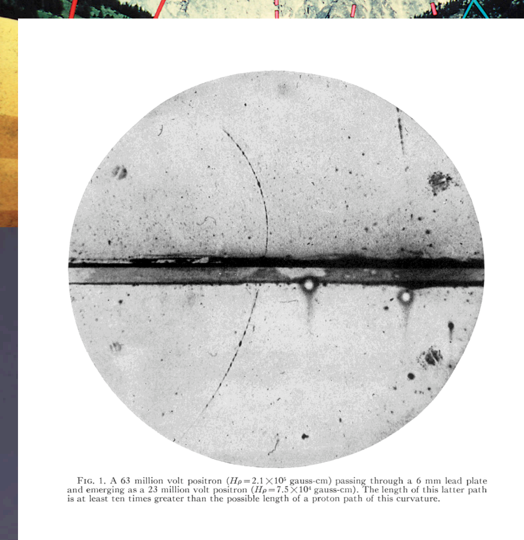
η^*

Ω^-

Thomson's
"electron"



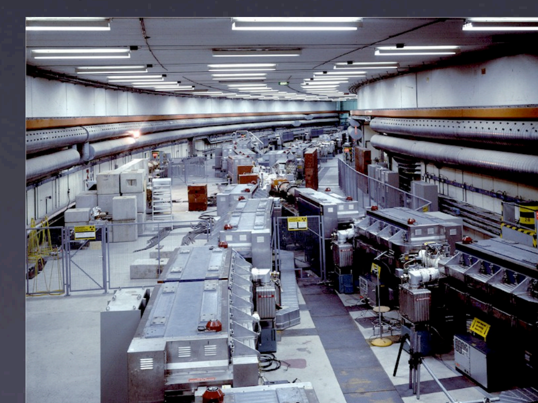




Antimatter!

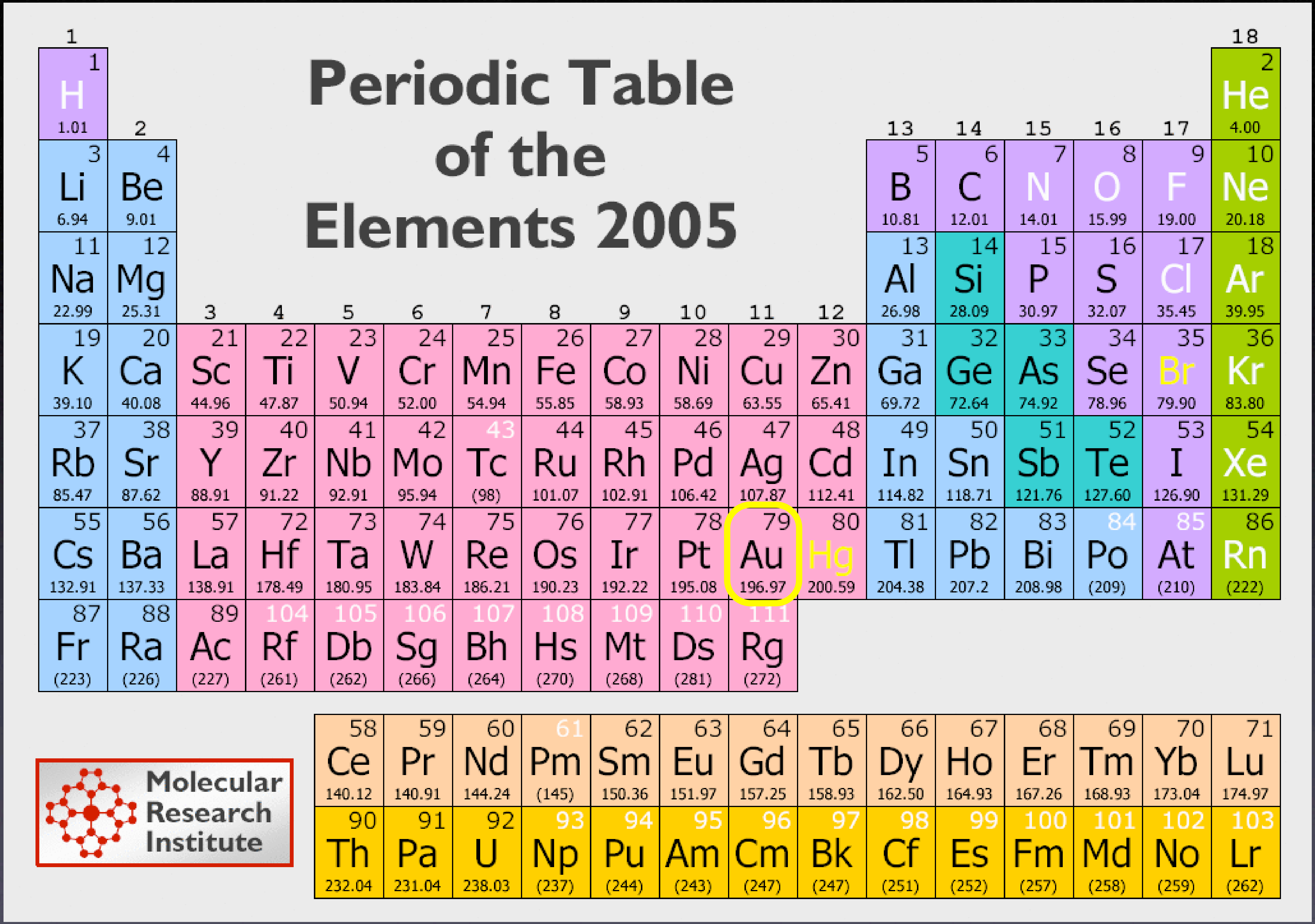
BNL

Berkeley



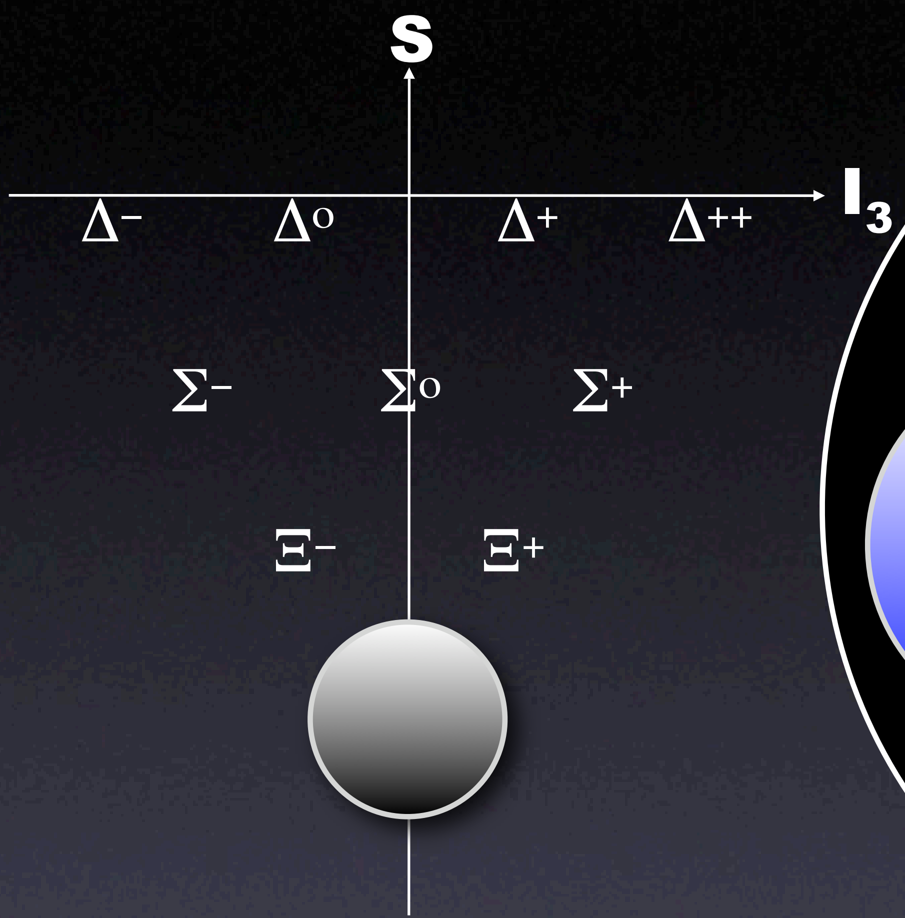
BNL AGS

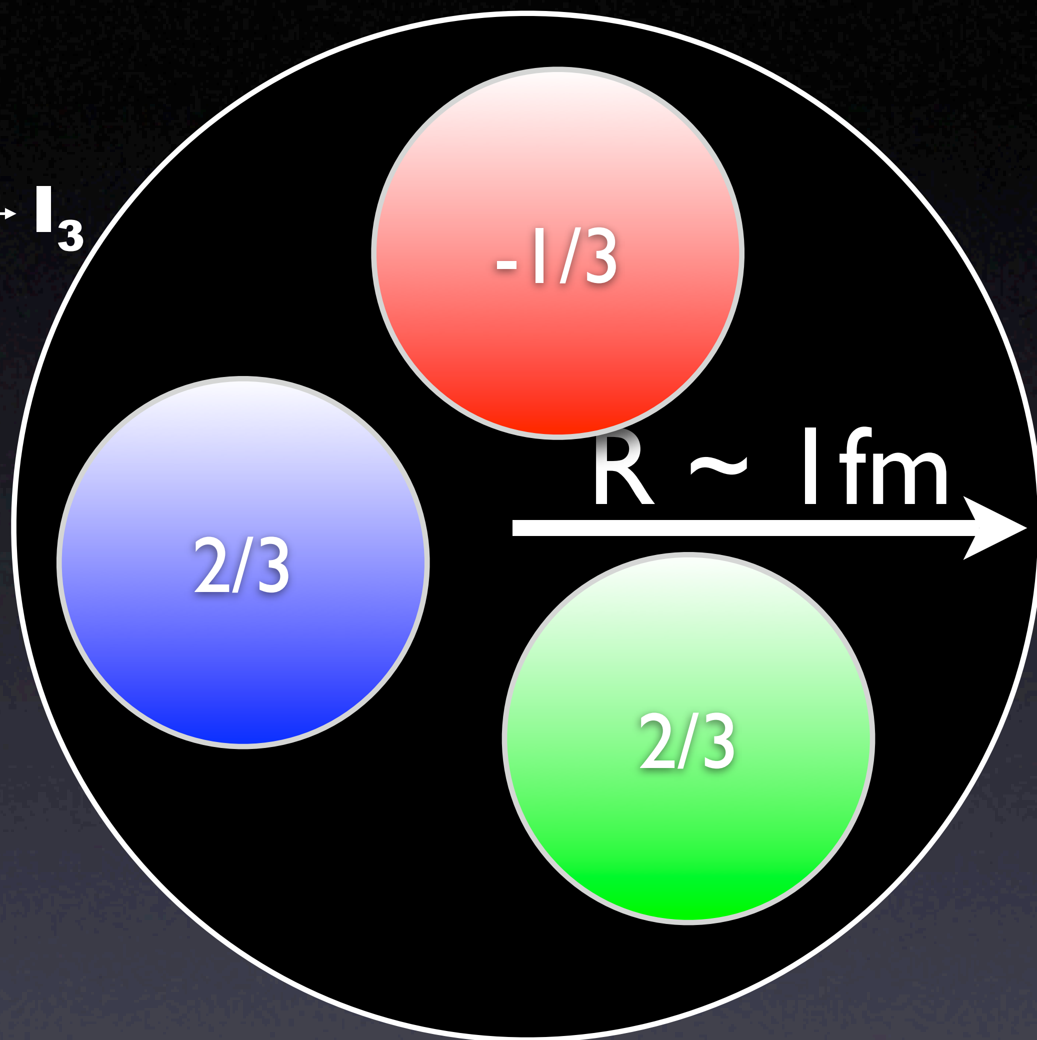
With new detectors and machines, many new particles were discovered!



The periodic table is a testament to the composition of nuclear species (even without knowing their "insides"!)

Making Sense of the Zoo

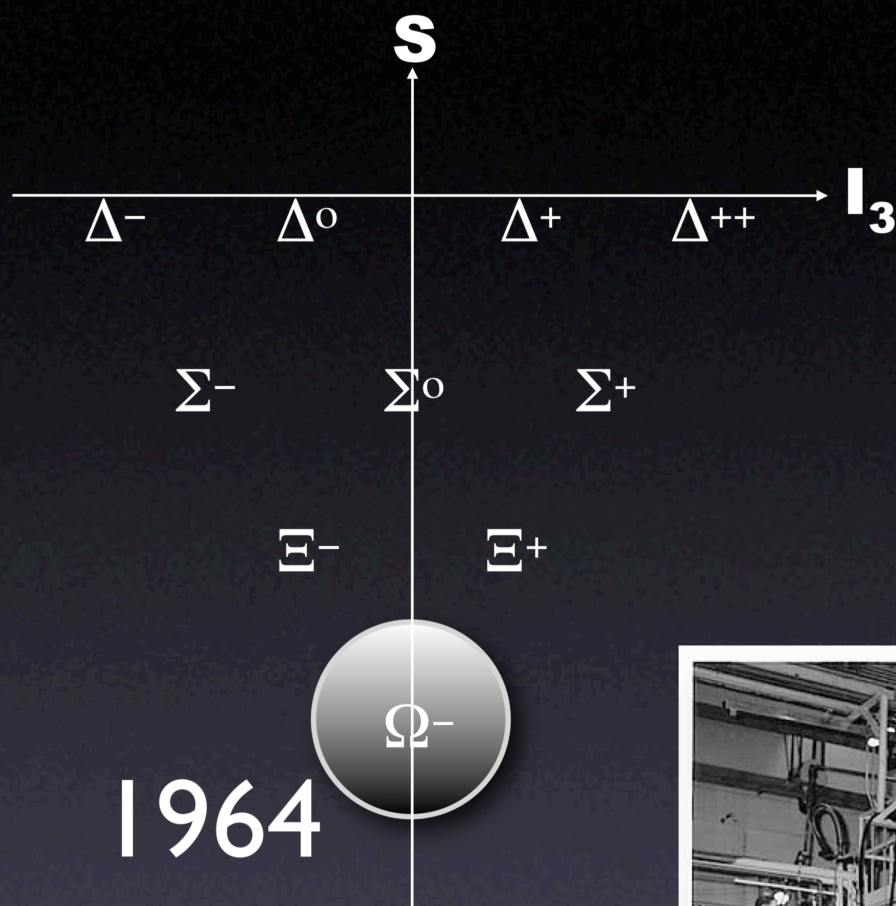


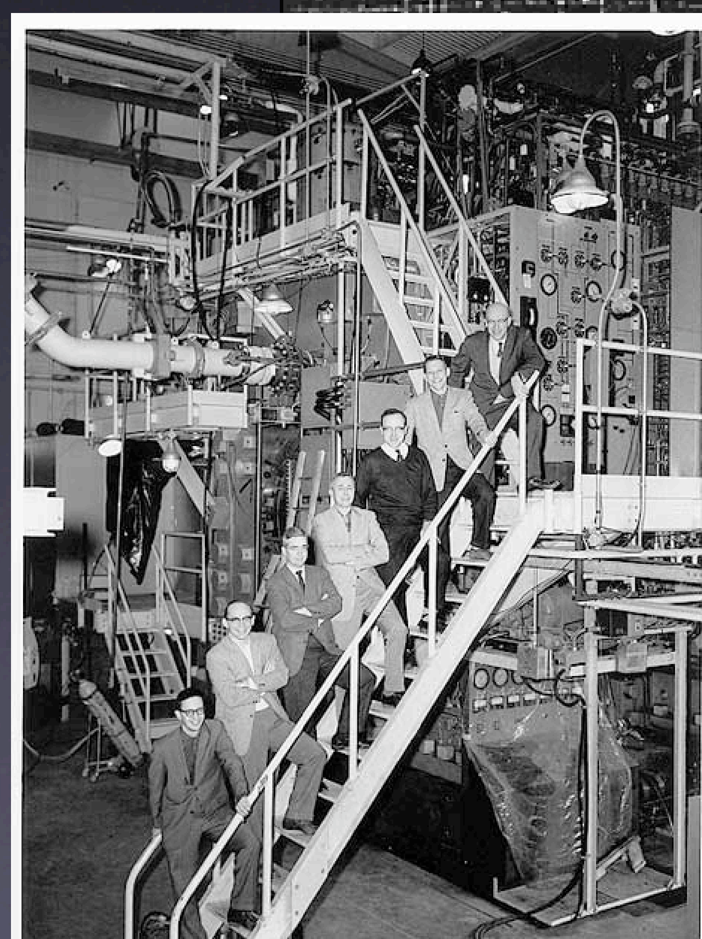


M. Gell-Mann

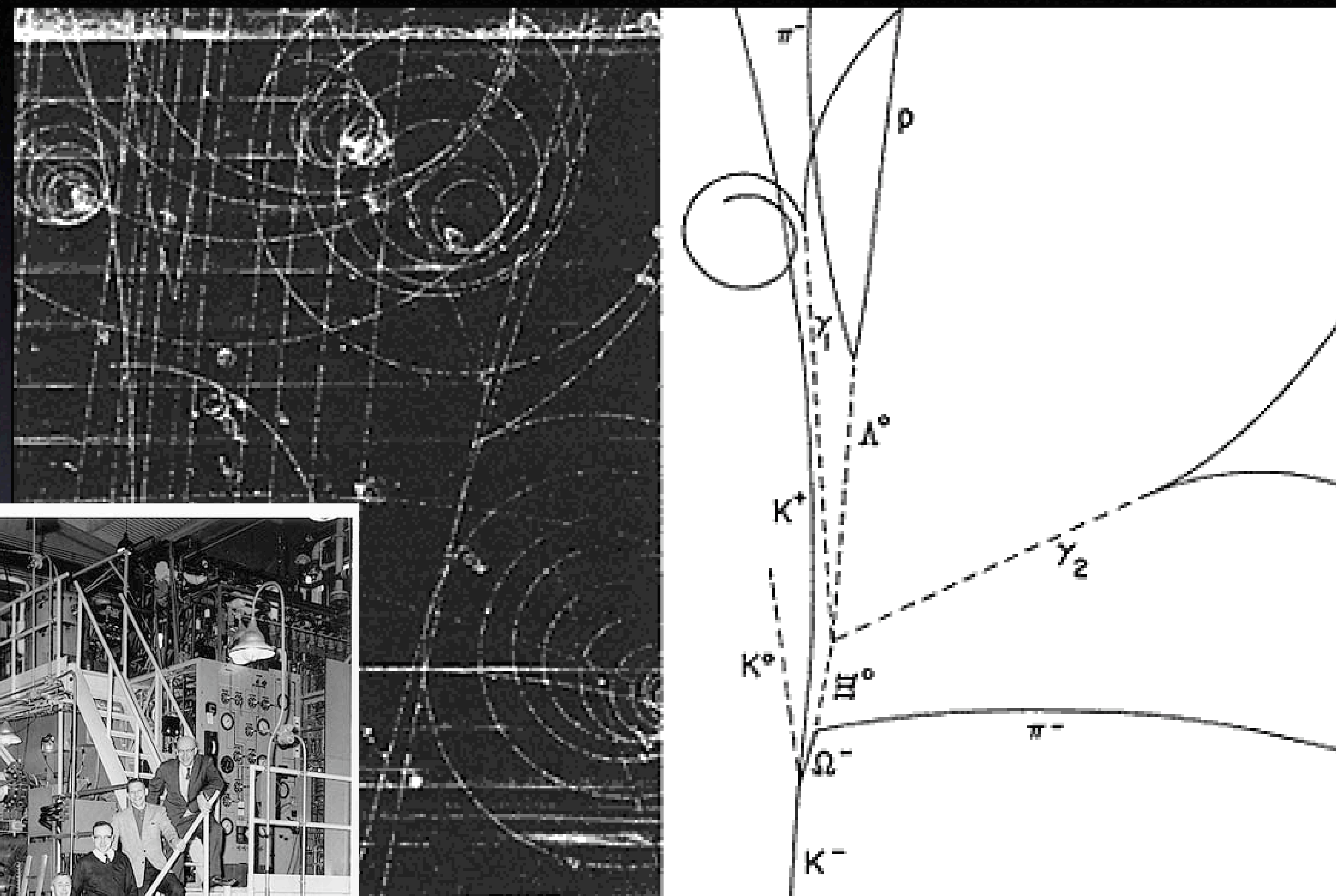
Gell-Mann and Ne'eman proposed "quarks" as a way to understand the particle zoo, kind of like the way the periodic table makes sense of the known elements

The Quark Model





Omega-minus group: (T to B) Ralph Shutt, Jack Jensen, Medford Webster, William Tuttle, William Fowler, Donald Brown, Nicolas P. Samios

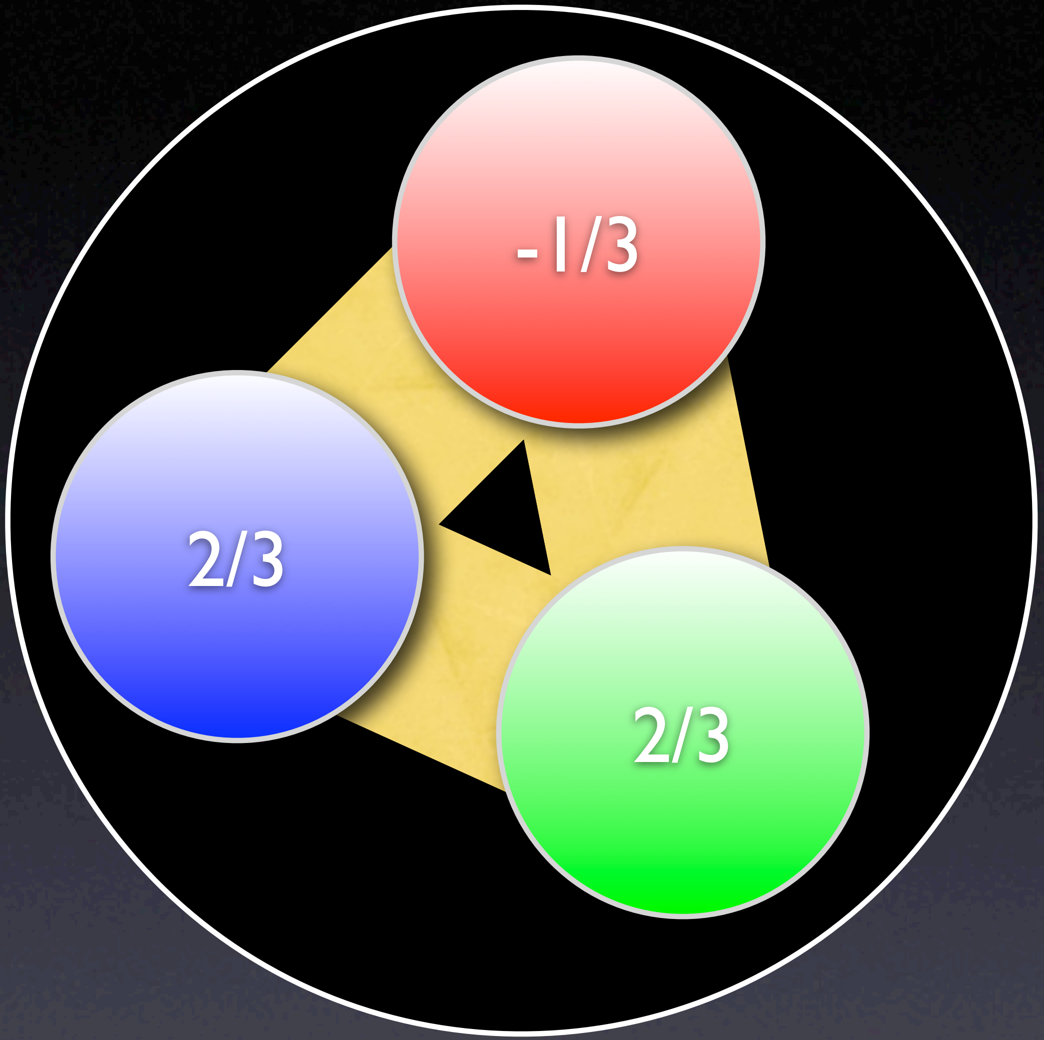


Omega Particle @ BNL

Verified quark model!

The Quark "Glue"

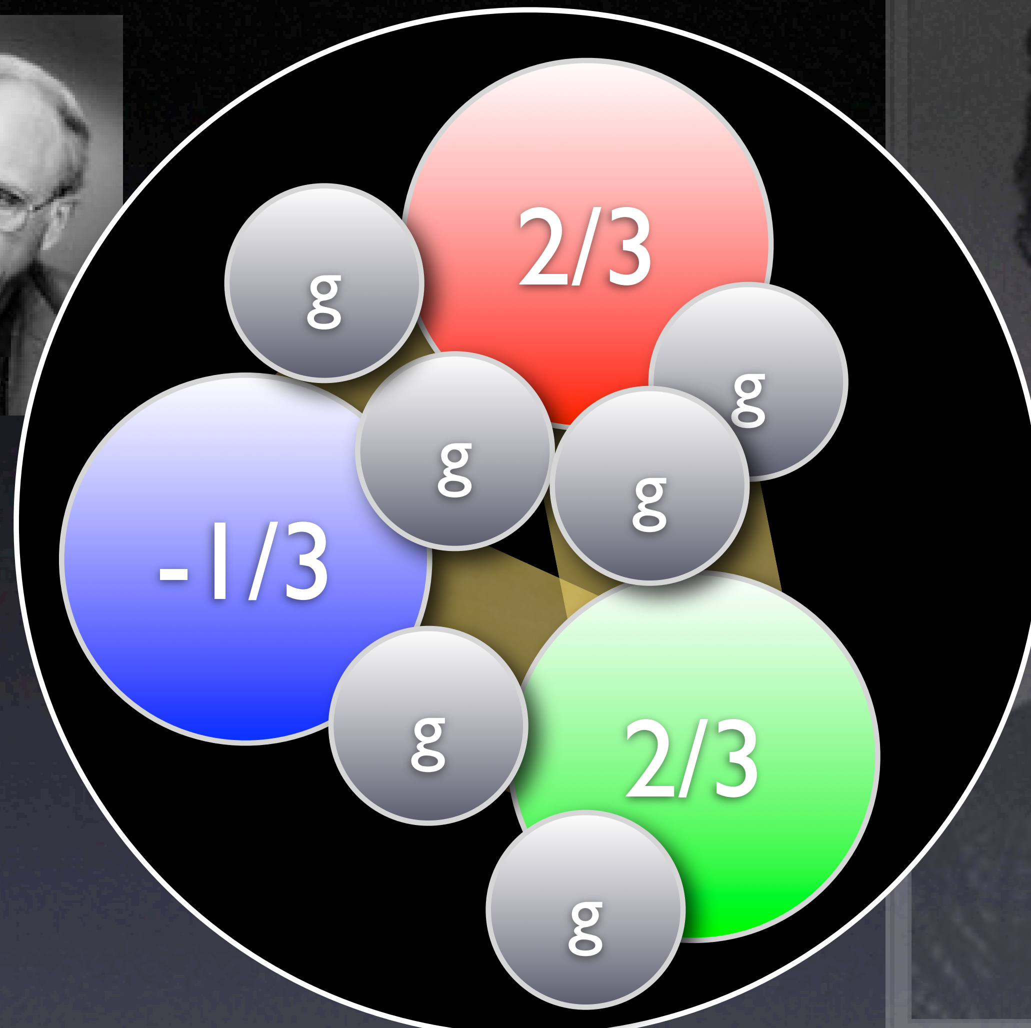
Yang & Mills
(1954 BNL)



After quarks were discovered theoretically and experimentally, it was a matter of time until people began to understand the forces (i.e fields) holding them together

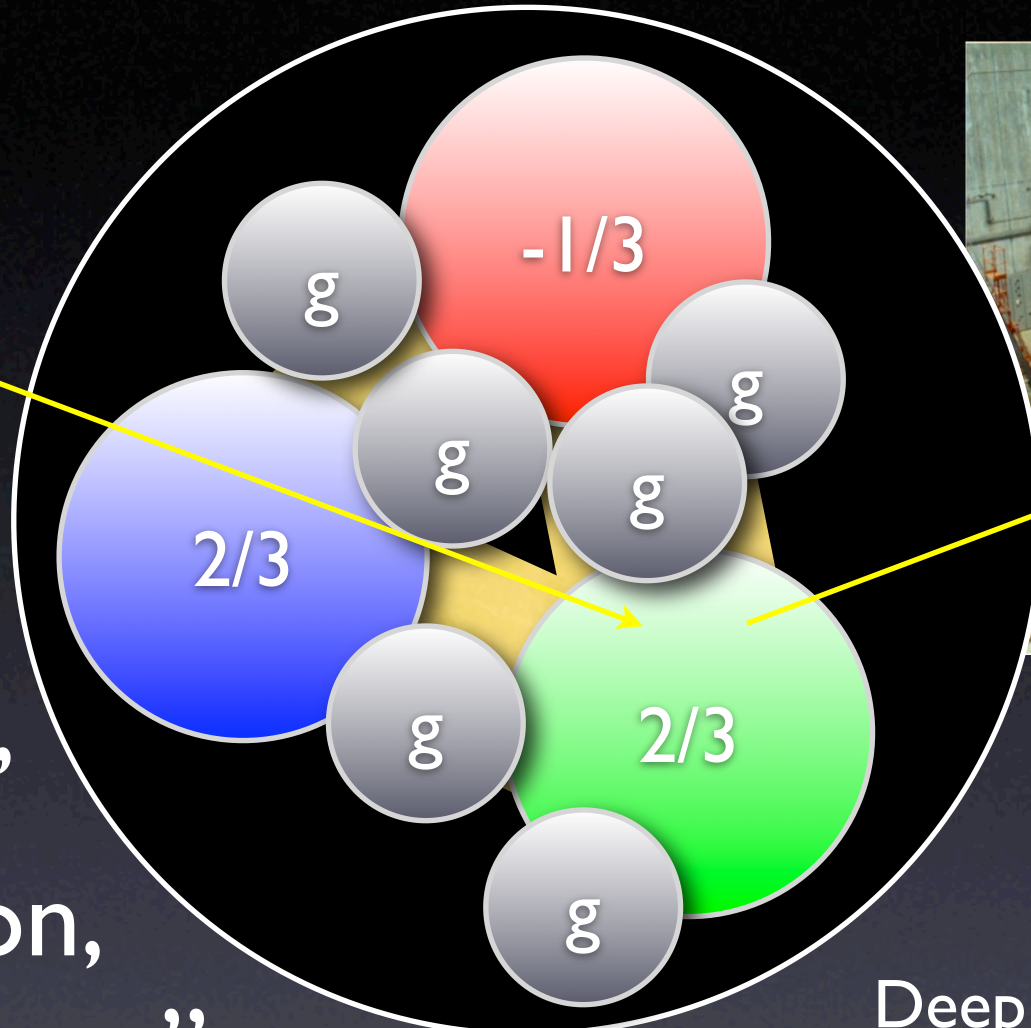
Quantum Chromodynamics

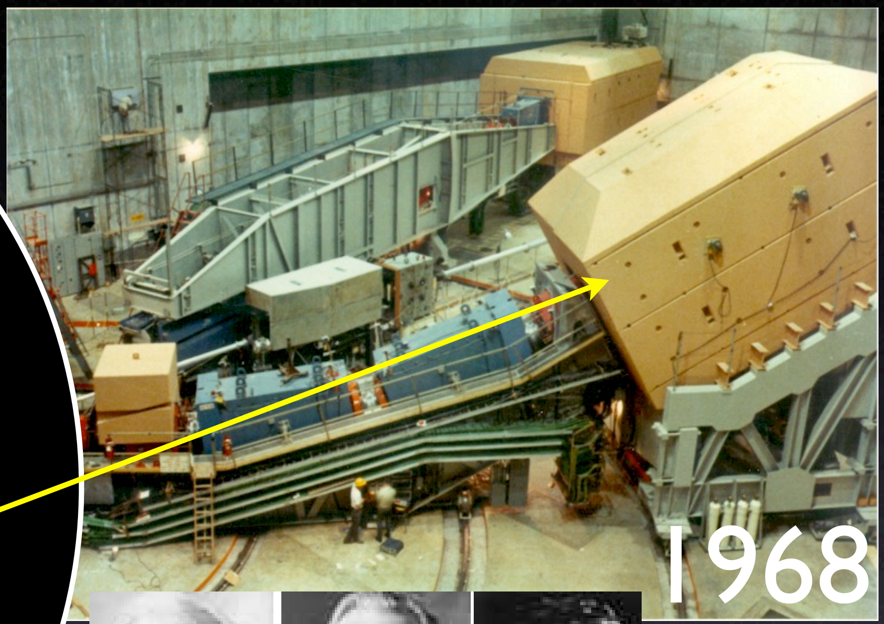
2004 Nobel Prize

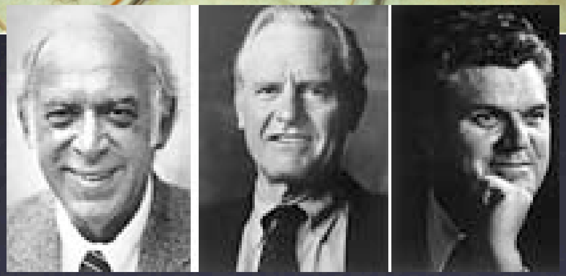


Just as photons are the "particles" of the electromagnetic field (1905!), the **"gluon"** is the carrier particle of the "color" field of QCD, **Quantum Chromodynamics**

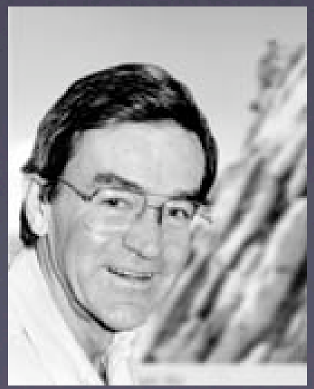
Probing a Proton



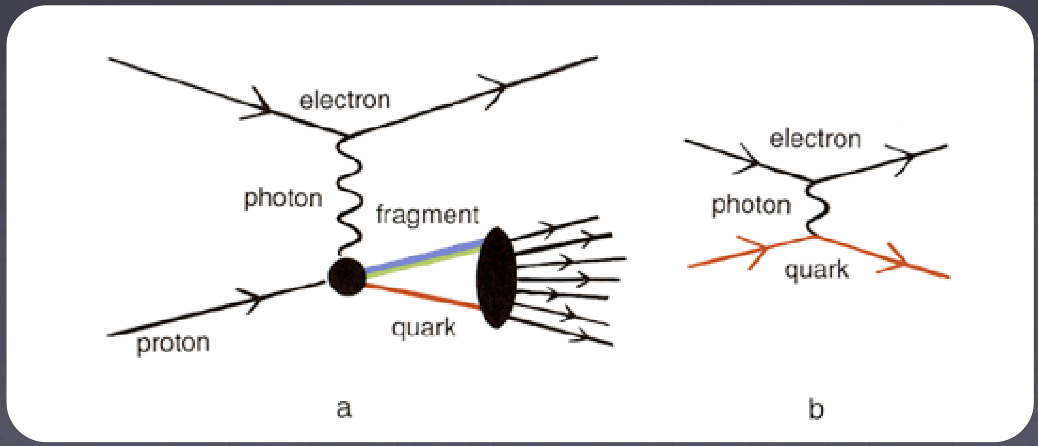




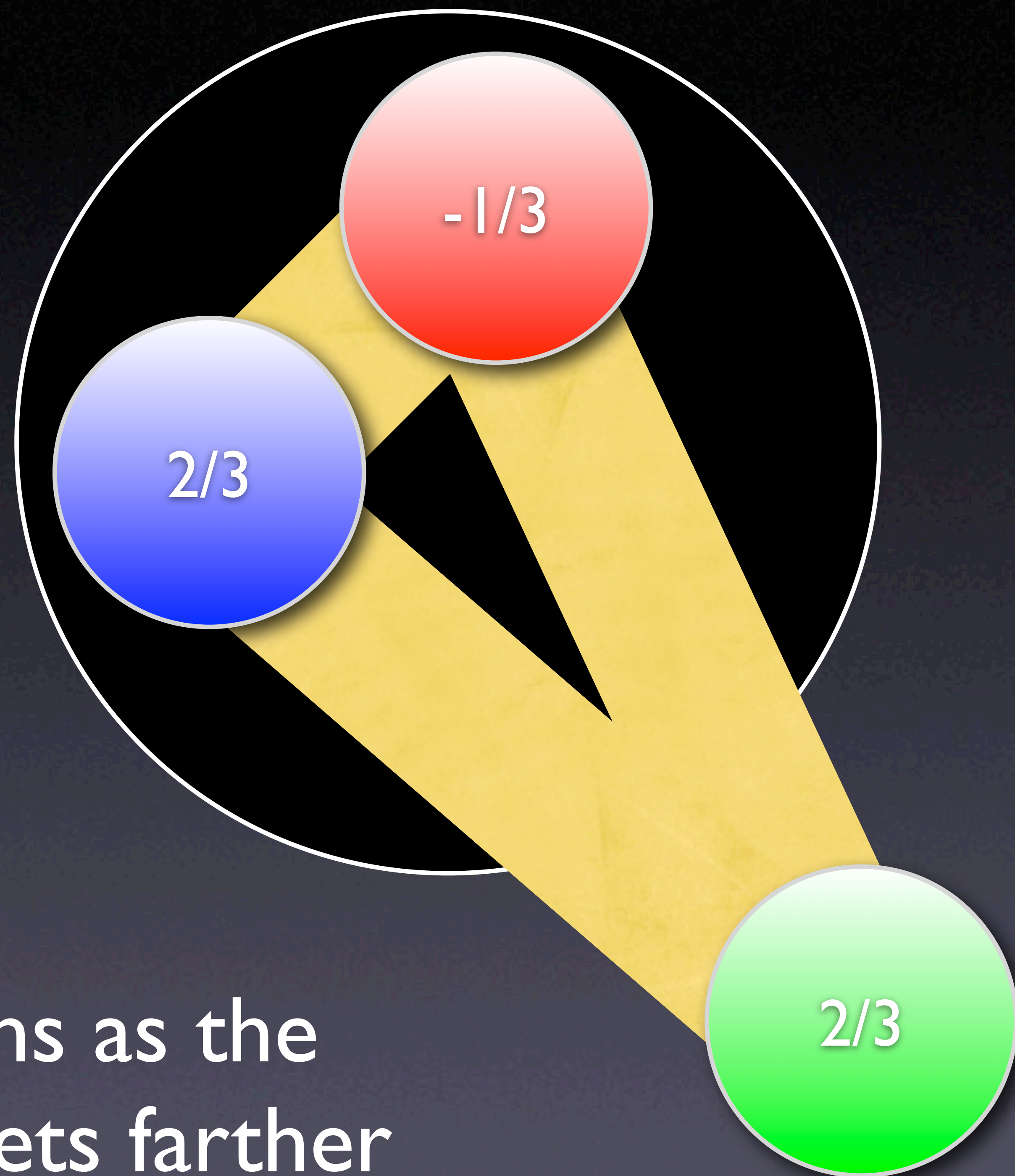
If we “look” inside a proton,
Can we see “pieces” of it fly out?



Deep Inelastic Scattering @ SLAC

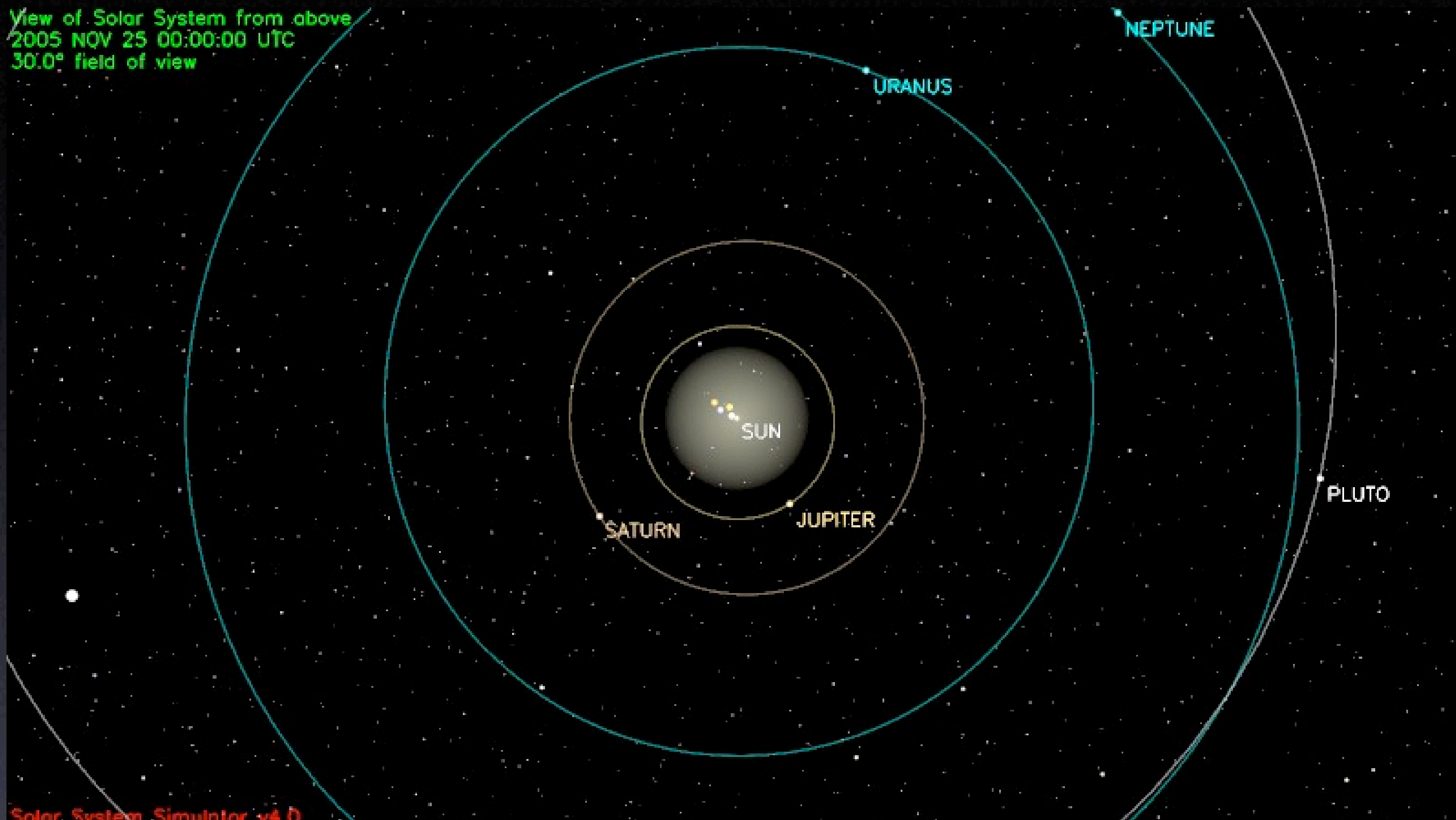


Probing a Proton



What happens as the struck quark gets farther from the proton?

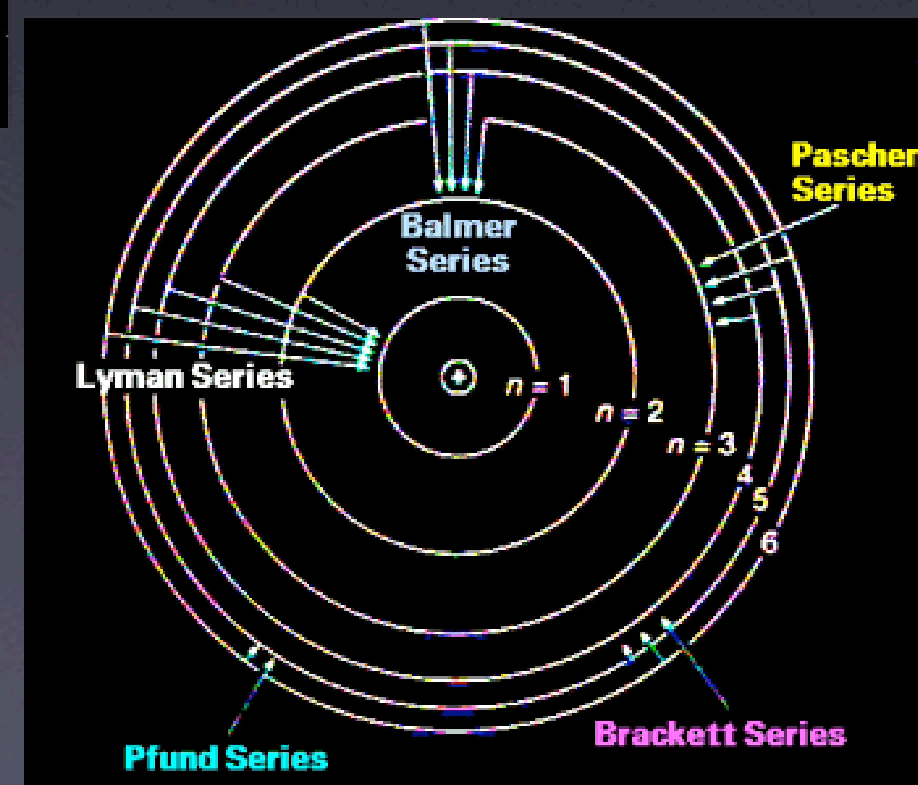
Gravity & E&M



Gravity & Electromagnetism holds much of our world together (except the nucleus and nucleon)

The two most important forces in our everyday lives get weaker as the particles get farther away from each other!

$E \sim 1/r$, $F \sim 1/r^2$

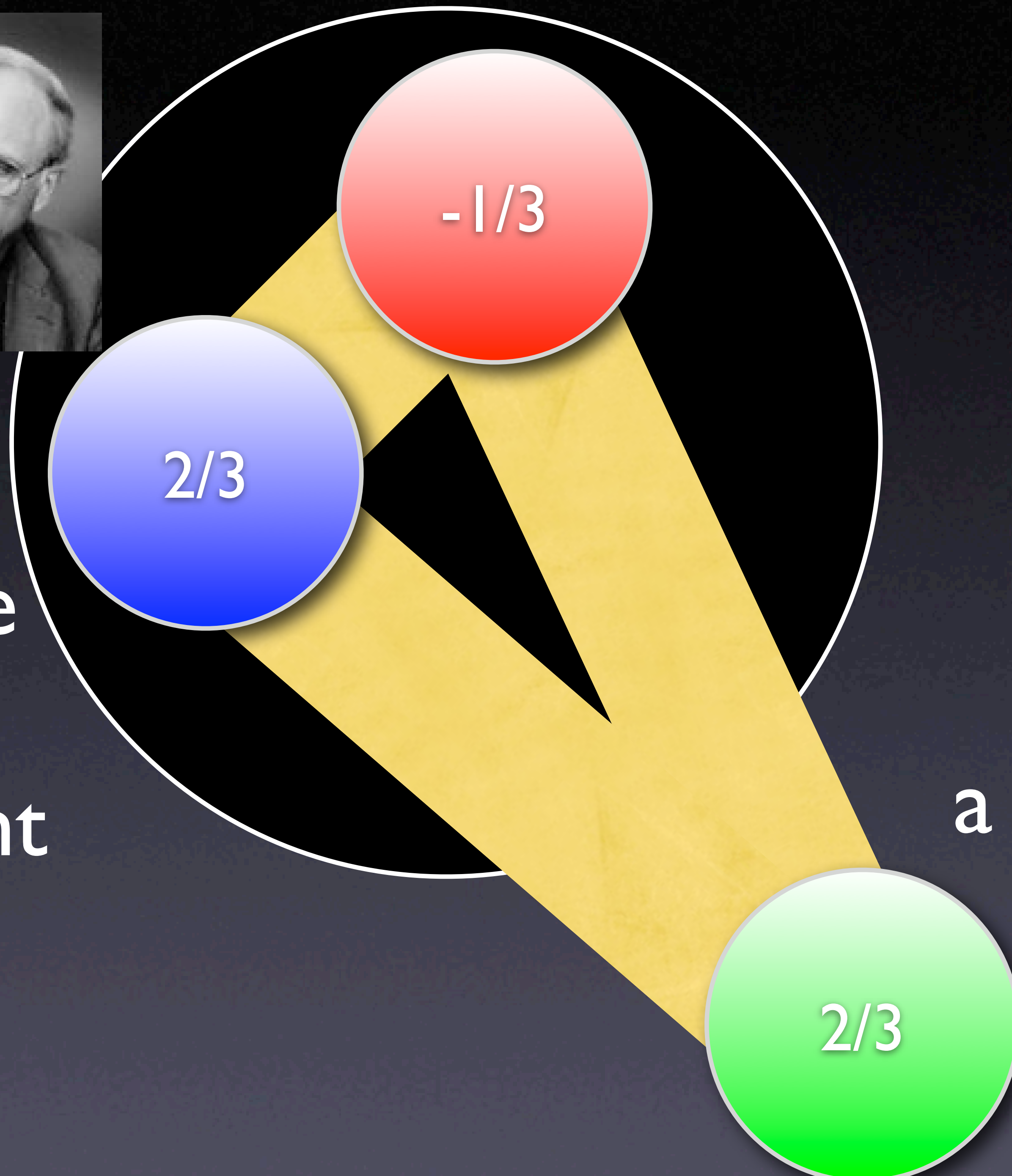


http://www.mps.mpg.de

Probing a Proton

QCD

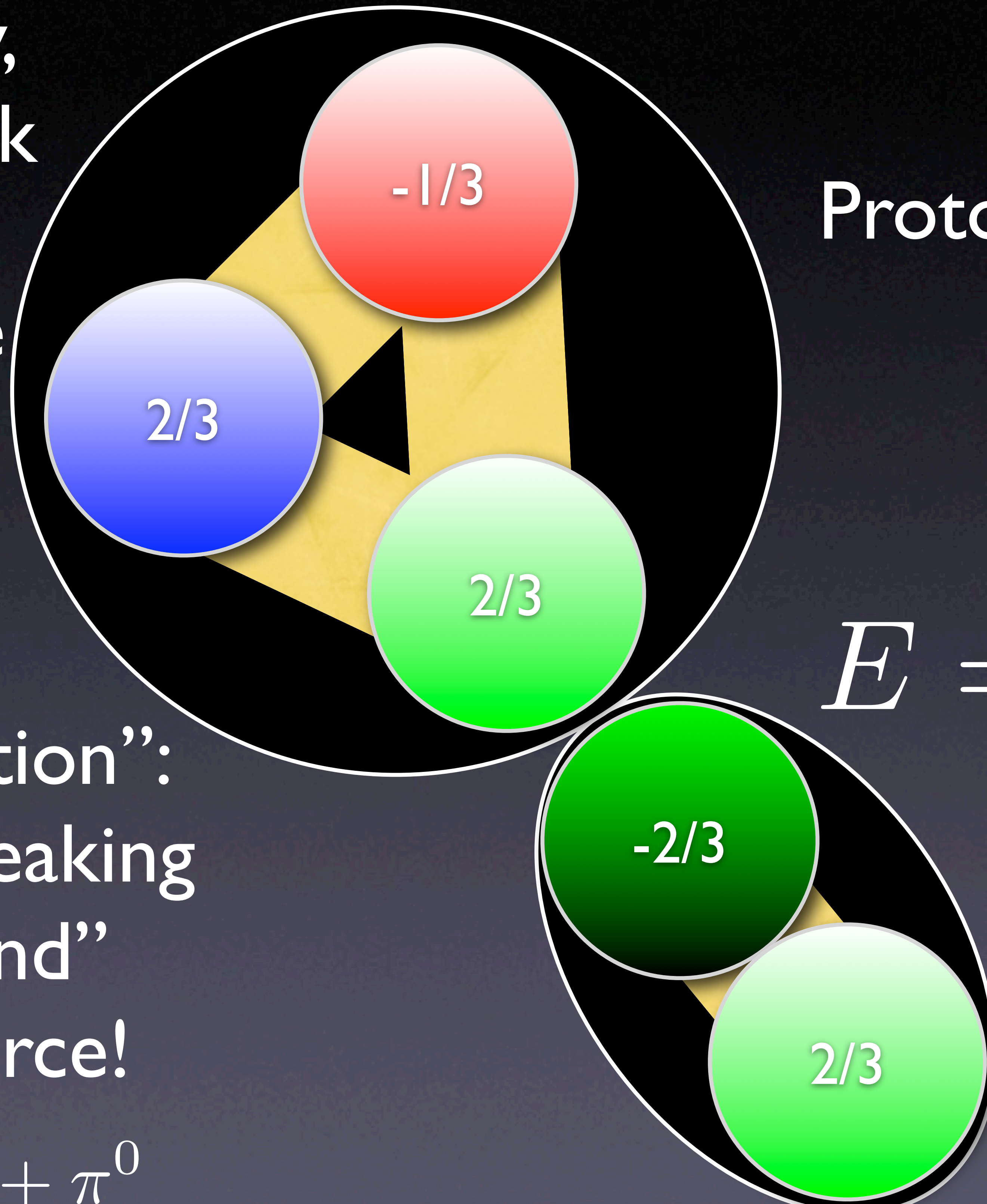
predicts that the force between quarks is constant with increasing distance



Energy ~ r similar to stretching a rubber band

SNAP!

Eventually, there's too much energy, and another quark and anti-quark "pop" out of the vacuum!



Proton

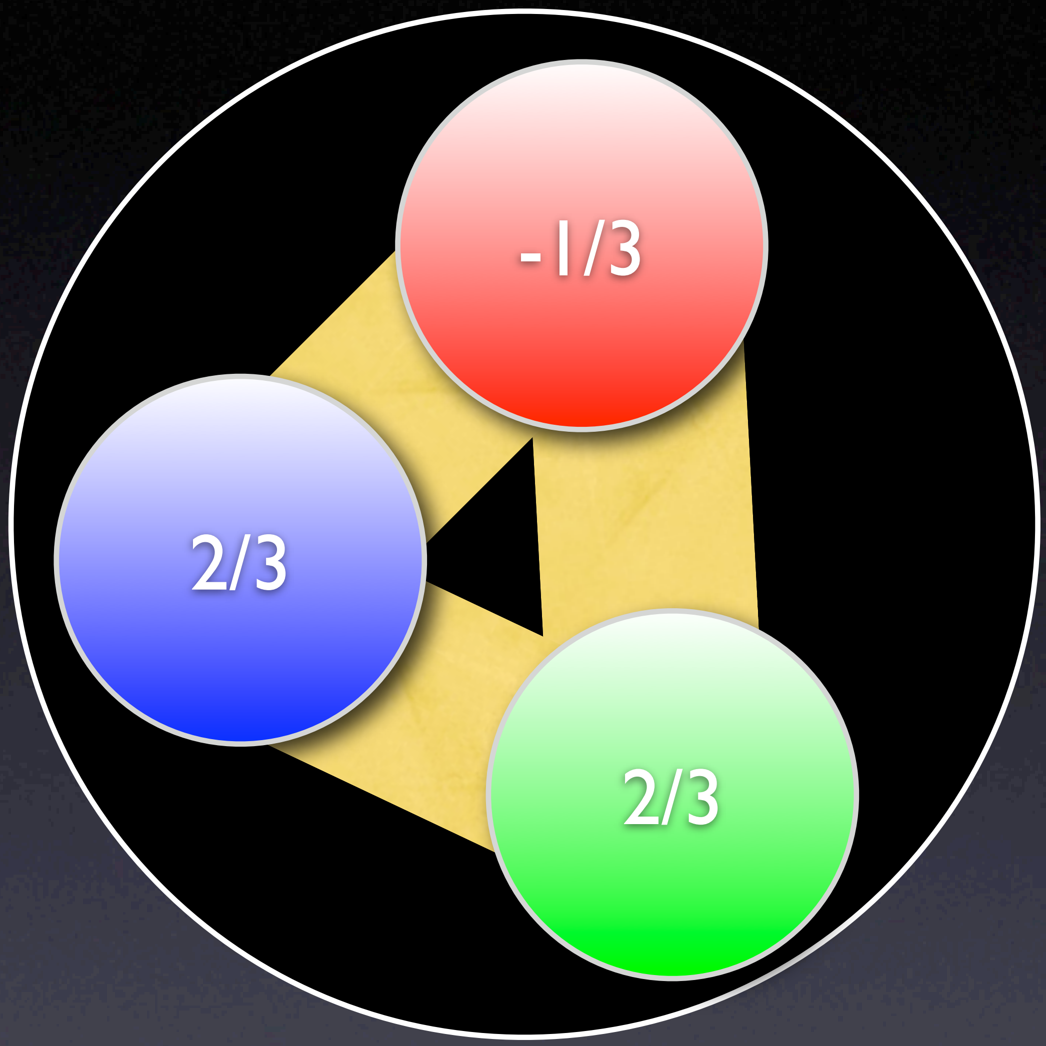
Pion

$$E = mc^2$$

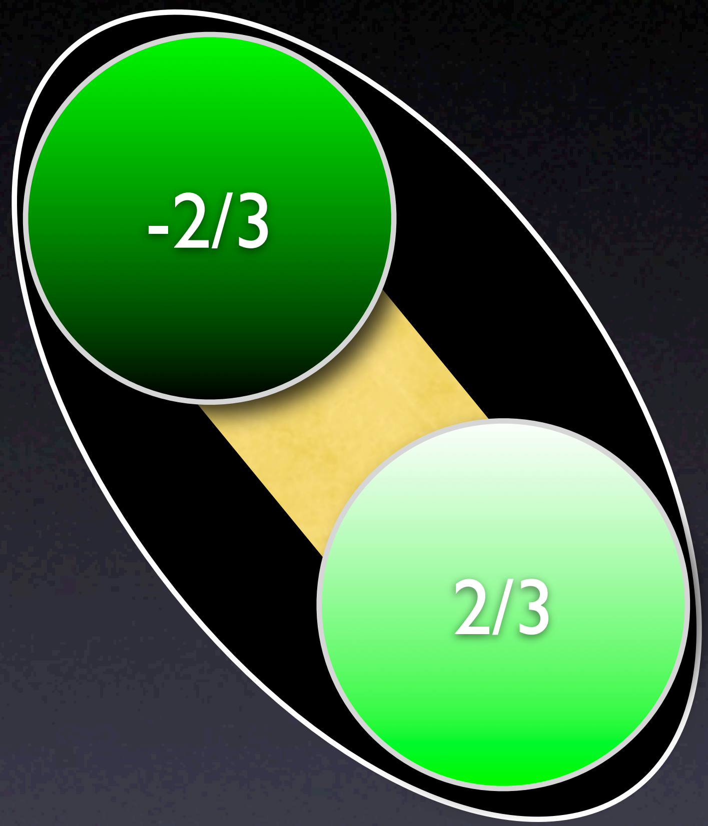
"Particle production": stretching and breaking the "rubber band" of the strong force!

$$e^- + p \rightarrow e^- + p + \pi^0$$

"Hadrons"



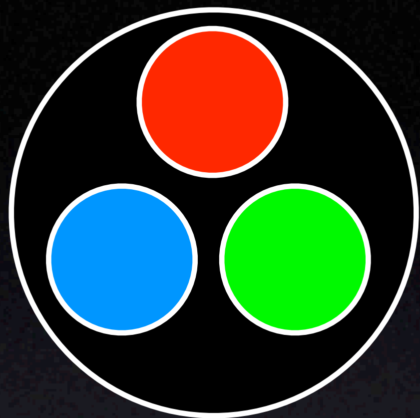
A "Baryon" is 3 quarks: flavors, charge, spin, mass & CONSERVED



A "Meson" is quark & anti-quark: flavors, charge, spin, mass

Quantum Chromodynamics requires "colorless" particles

A Zoo? More like an Ark...

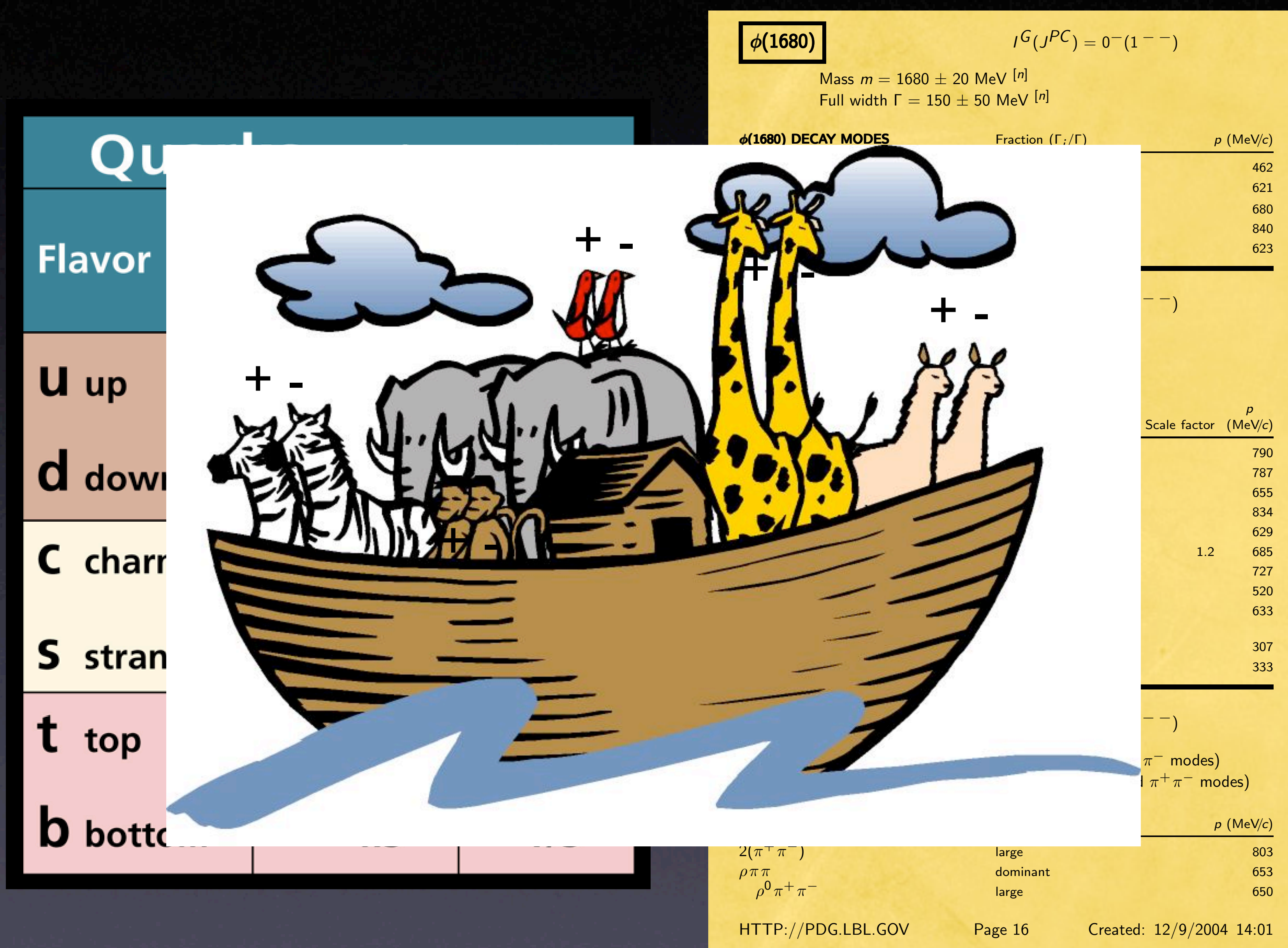


Σ Λ Ω Δ Ξ p n

Baryon
(3 q or q̄)

ω ρ π K ρ φ

Meson
(1 q & q̄)



1000's of "hadronic states" (particles & anti-particles) have been observed, many discovered here at BNL

Heating

In the early 1960's Rolf Hagedorn predicted that the bound state spectrum would rise indefinitely

→ Singularity at <u>limiting temperature</u>

$k_B T_H$~170 MeV

$$\rho(m) \sim m^a e^{m/T_0} \rightarrow Z$$

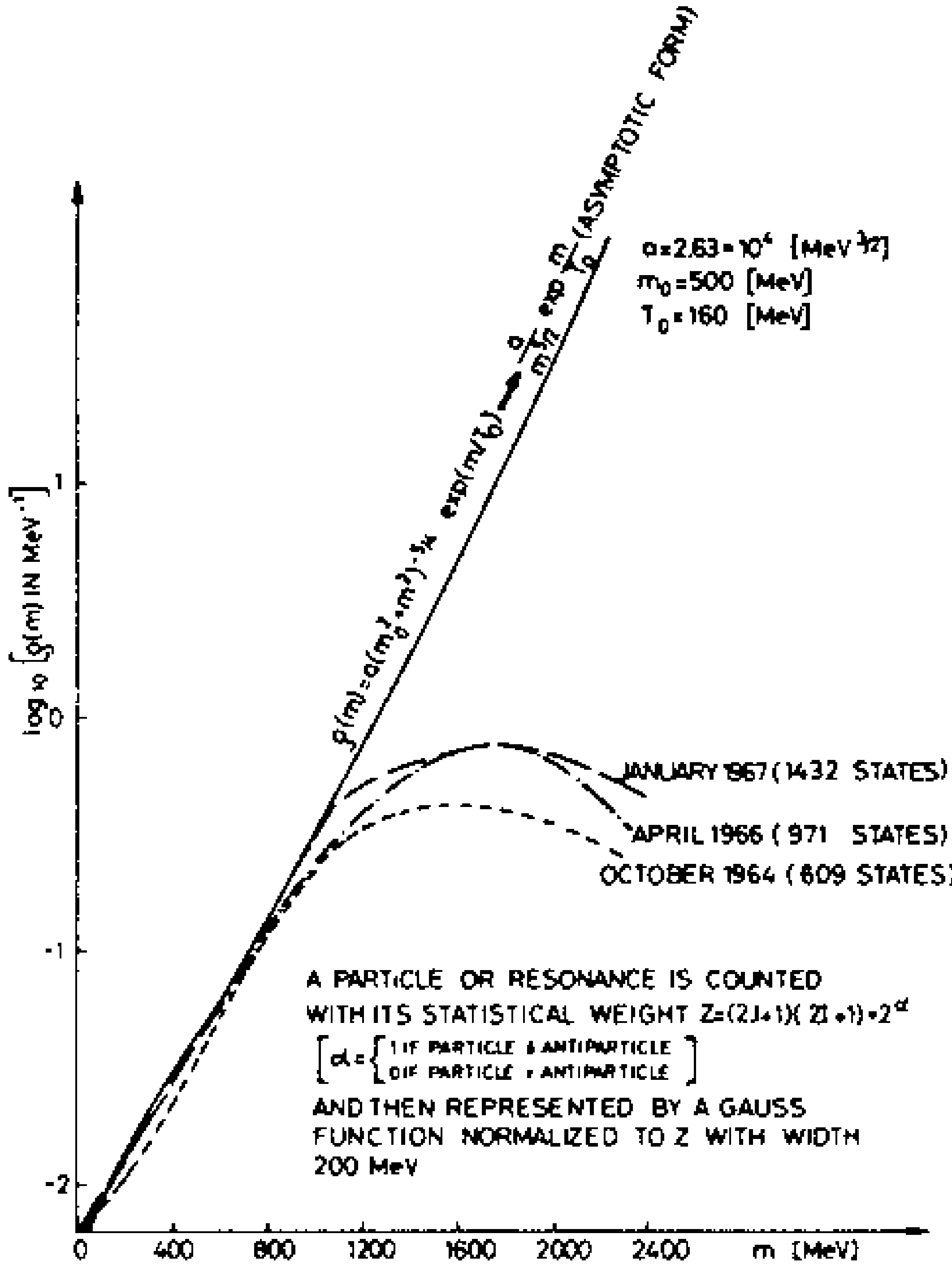
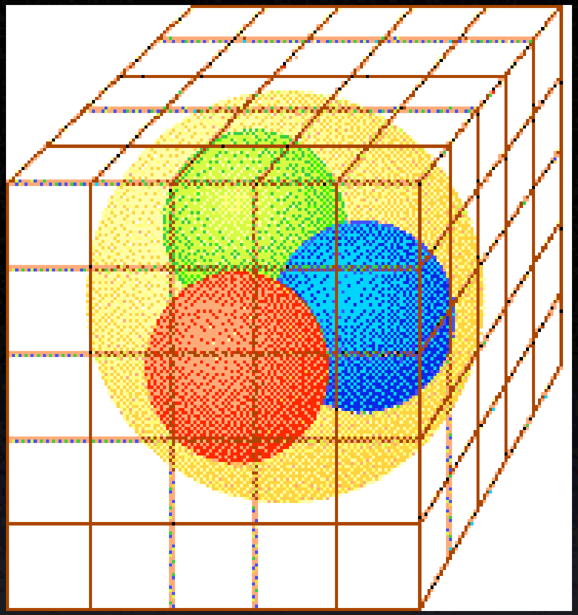


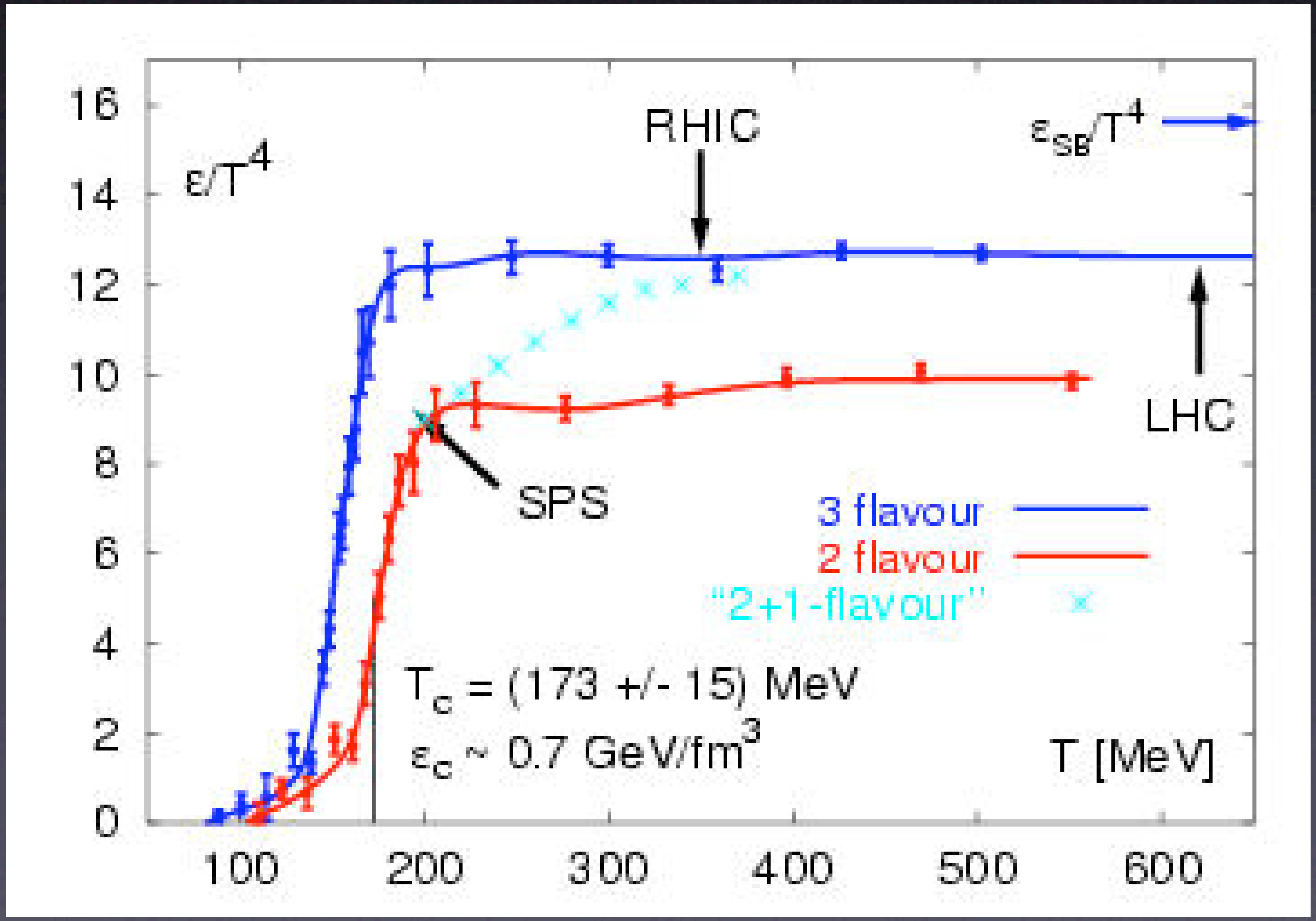
Fig. 3.1: The predicted and the experimental mass spectrum as it evolved from 1964 to 1967.

We've come a long way!

QCDOC 10 Teraflop computer
(BNL/Columbia/Edinburgh)



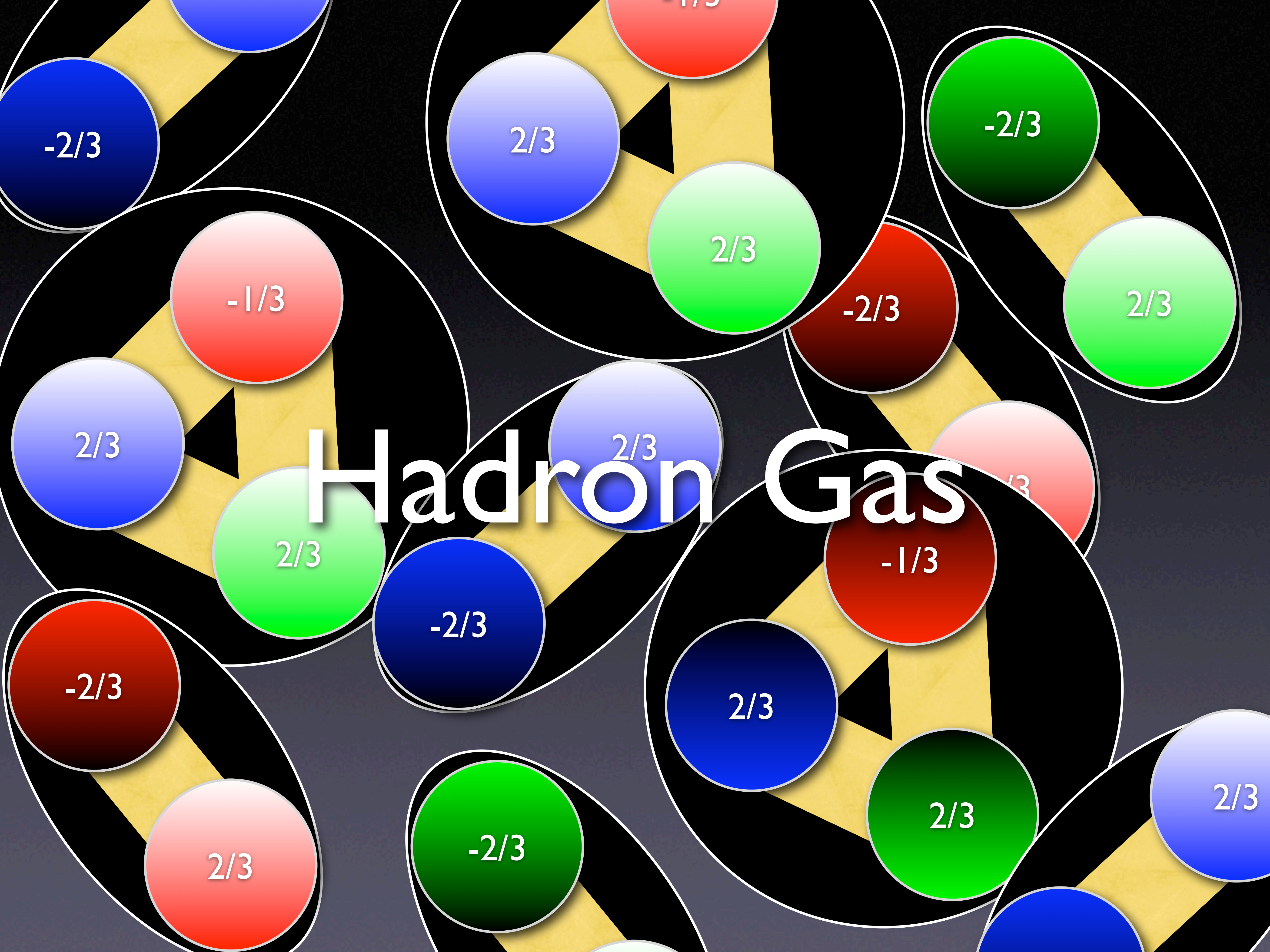
QCD is notoriously hard to solve for high temperature, so solved numerically on powerful machines!



M. Creutz, PRD21, 2308 (1980)

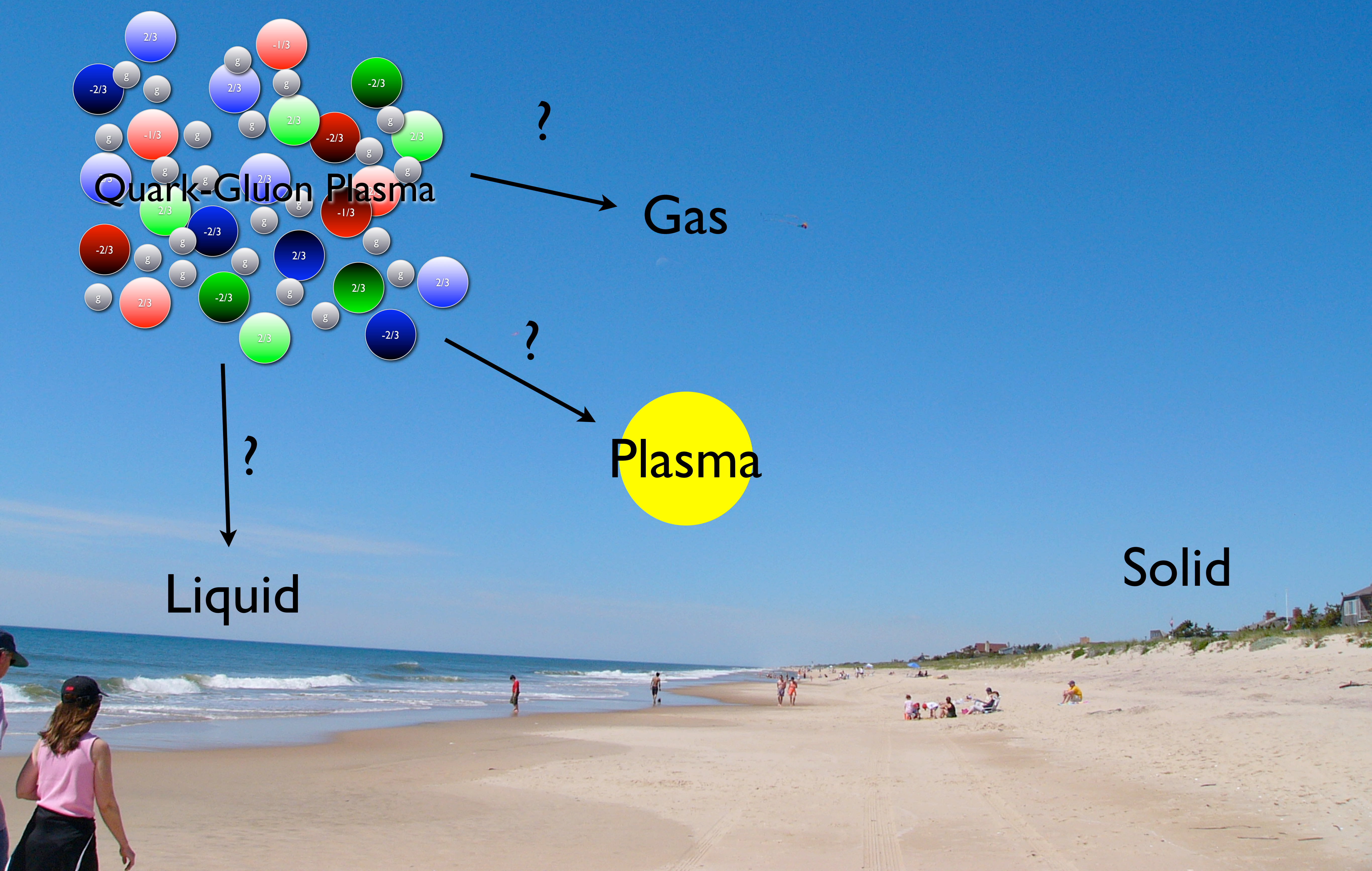
Years ago, it was discovered that there is a "jump" in the number of "degrees of freedom" at the Hagedorn temperature

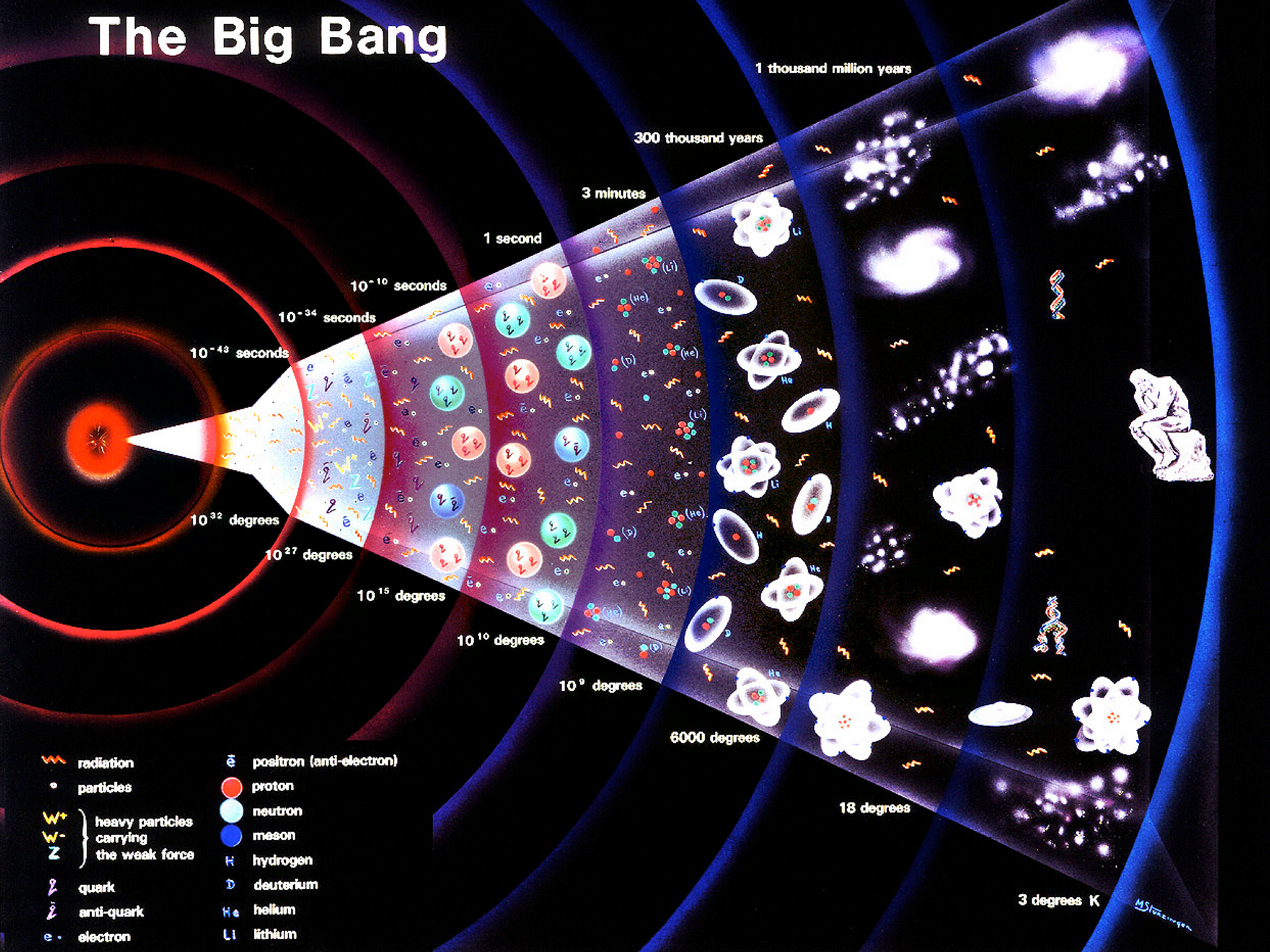
Hadron Gas



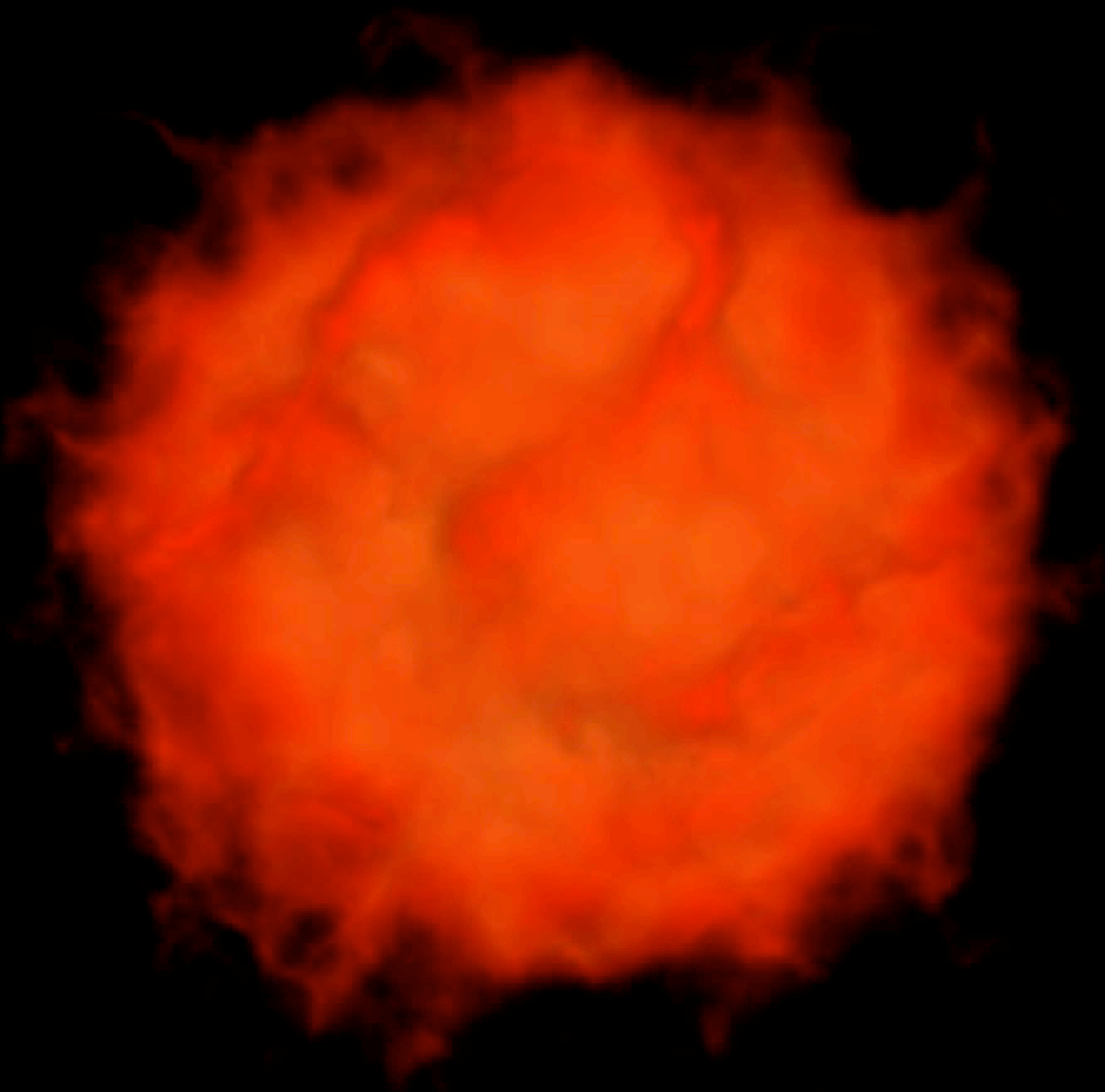
Quark-Gluon Plasma

QGP is a <u>new state of matter</u>




The Big Bang
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e · electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

What State of Matter?



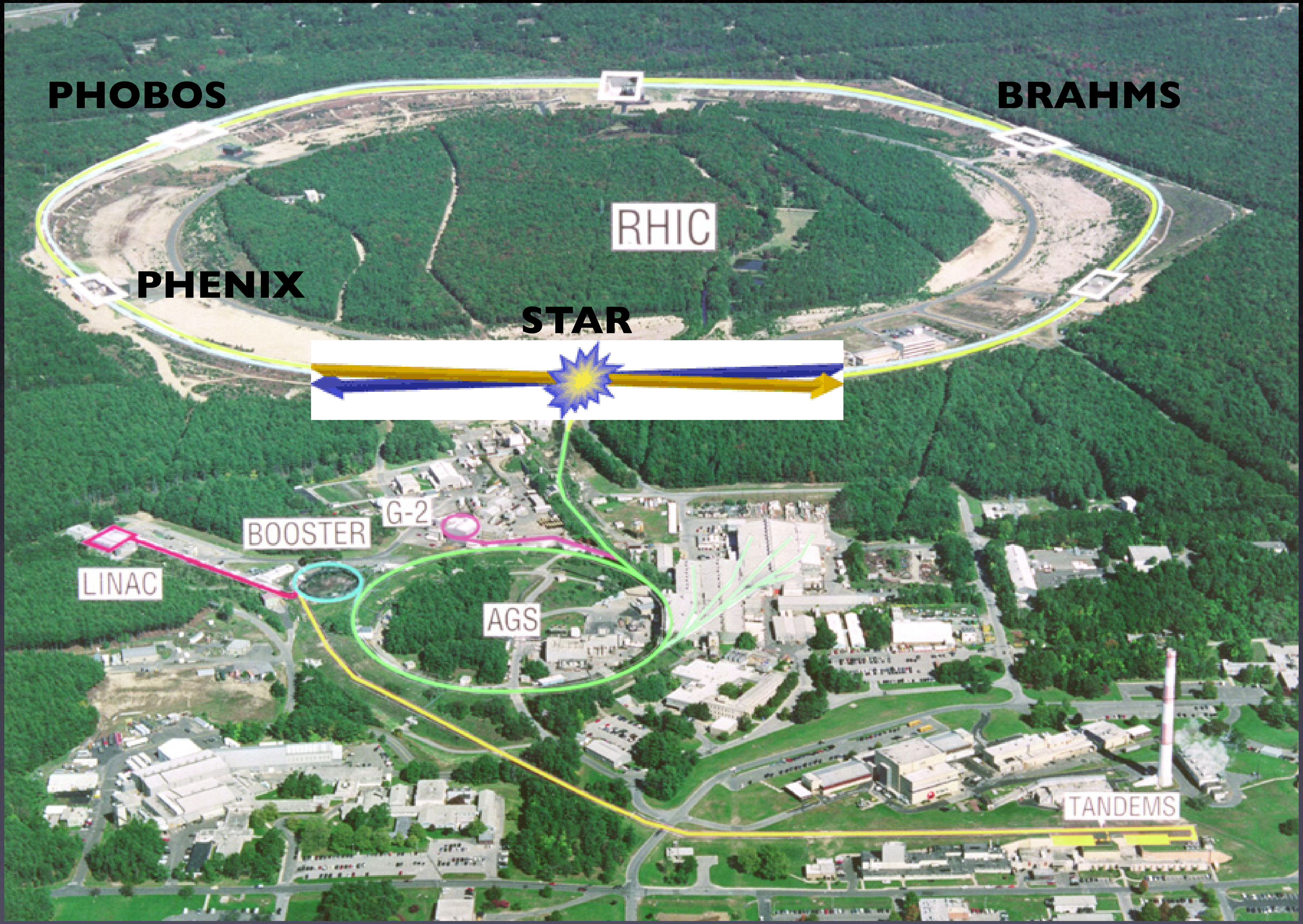
Does it evaporate,
like an ideal gas?

Does it flow,
like a (compressible) liquid?

RHIC

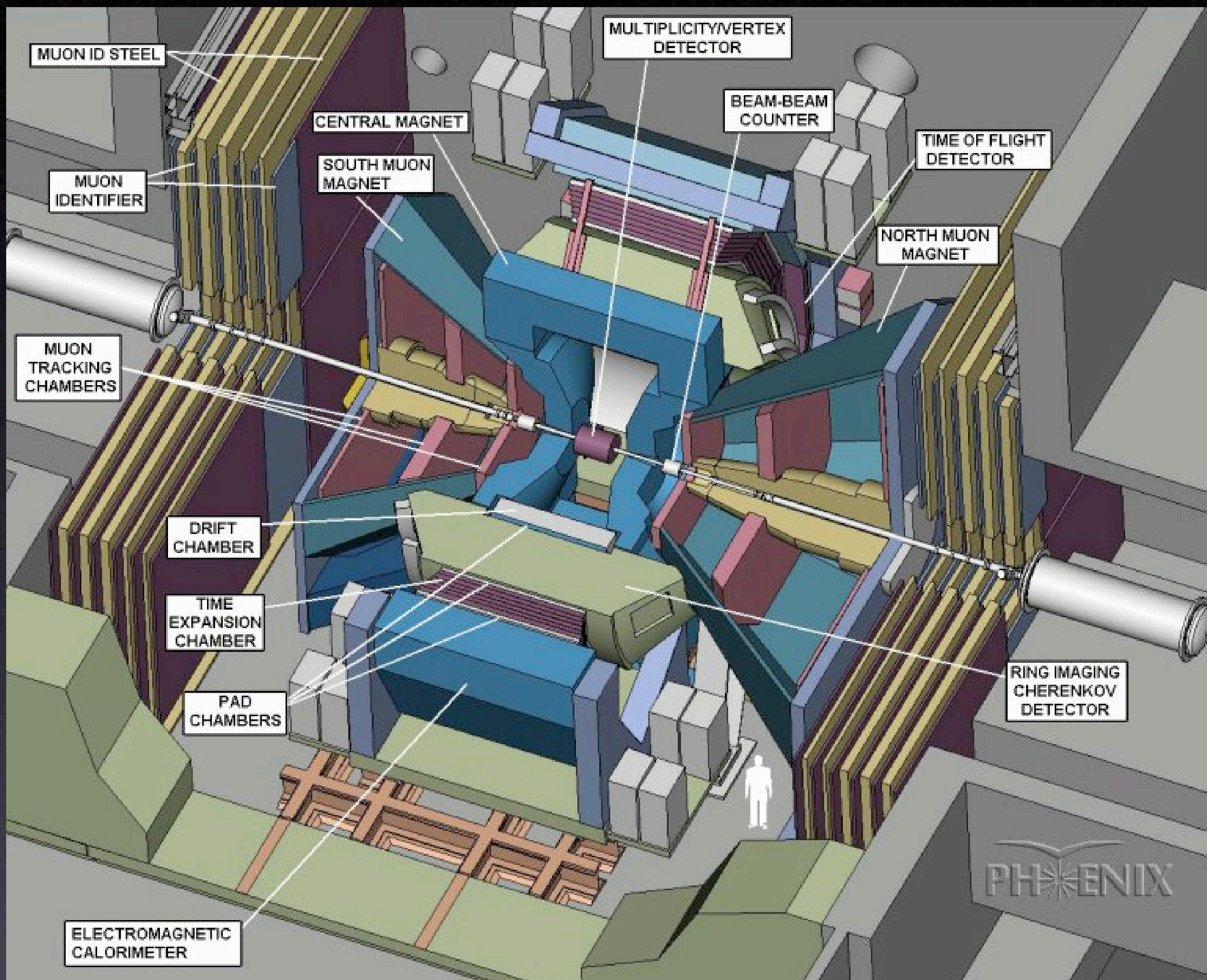
Relativistic Heavy Ion Collider

RHIC

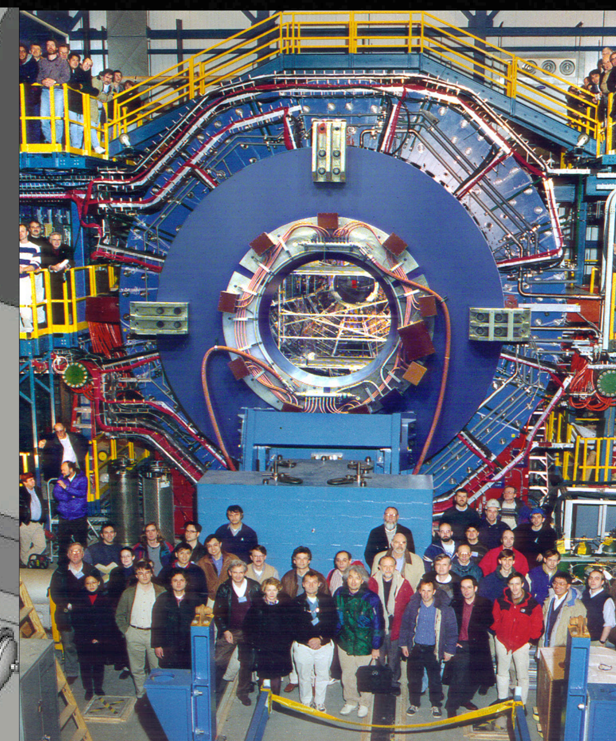


Relativistic Heavy Ion Collider

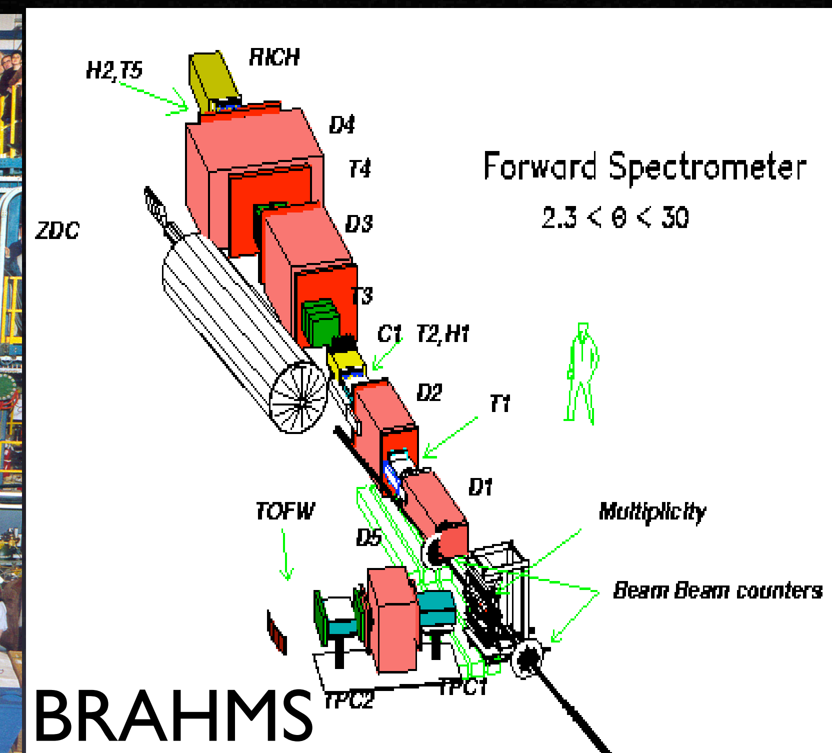
RHIC Detectors to Scale



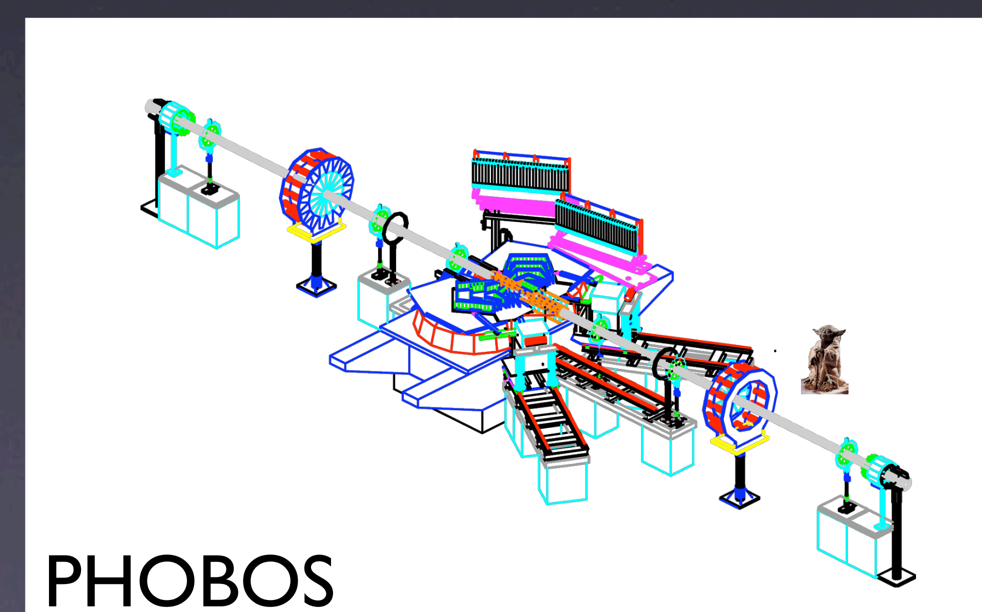
PHENIX



STAR



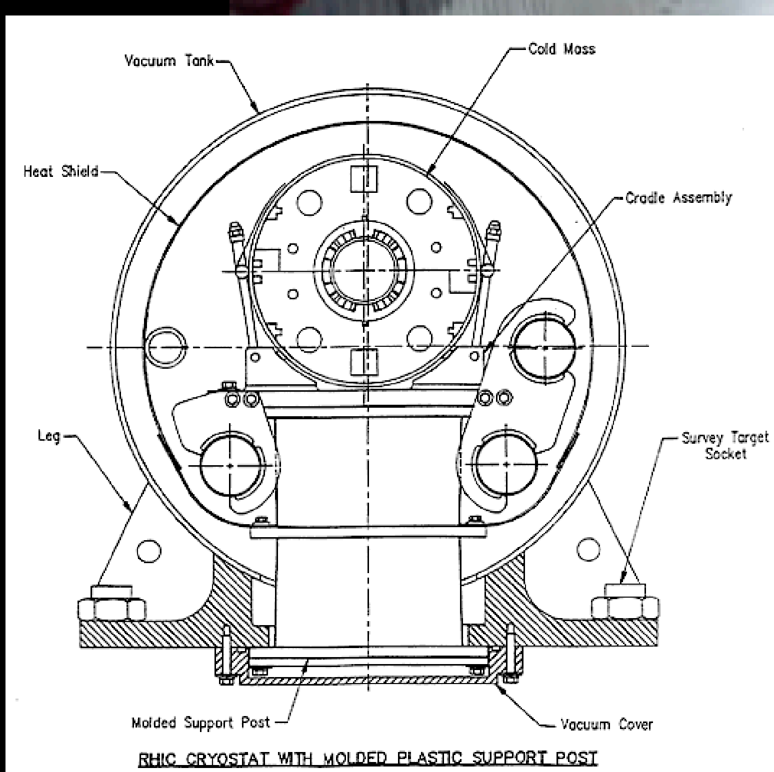
BRAHMS



PHOBOS

RHIC @ BNL

Tandems

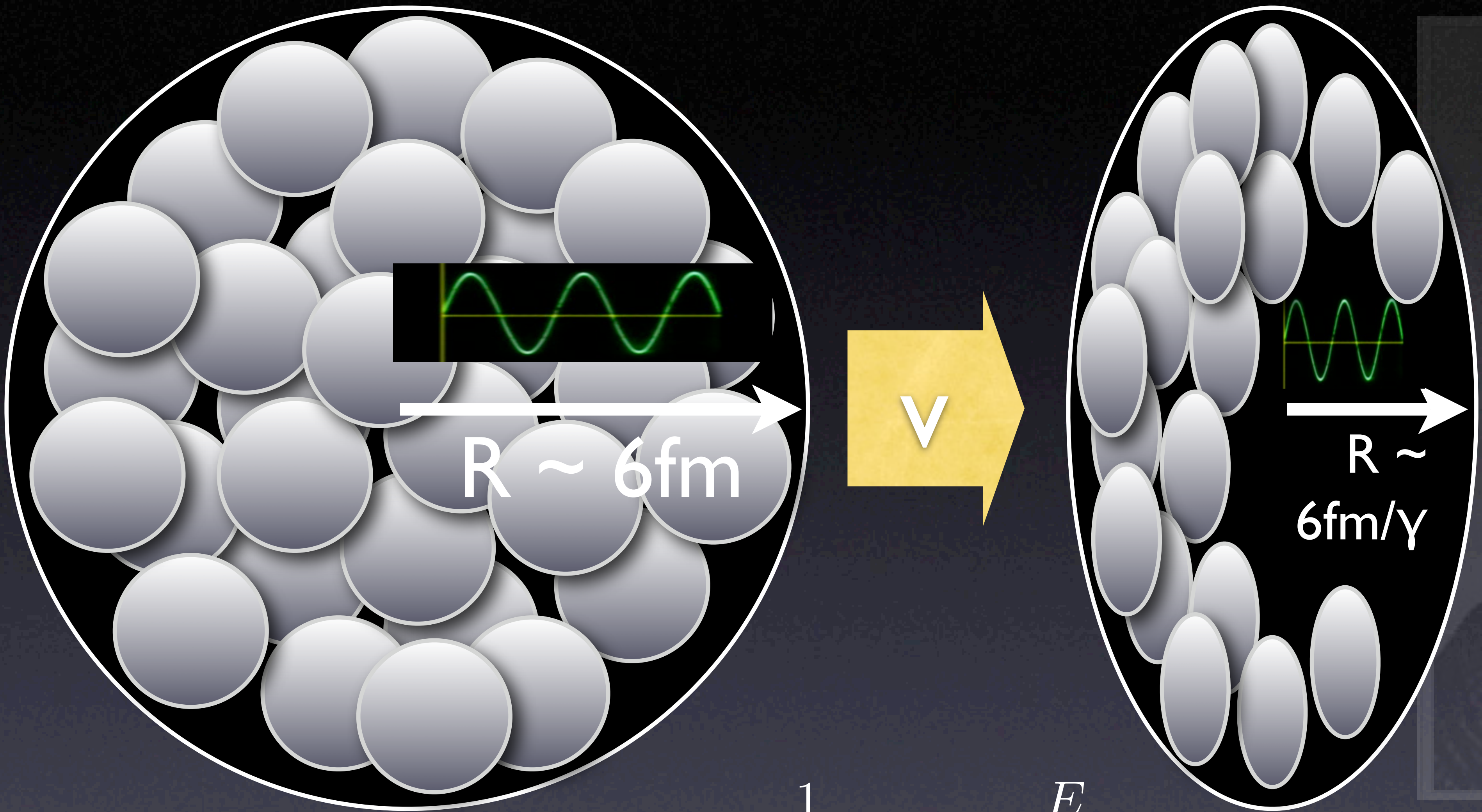


Collaboration w/
Northrop Grumman

Superconducting
Magnets (@ 4°K)

RF Cavities

Lorentz "Contraction"

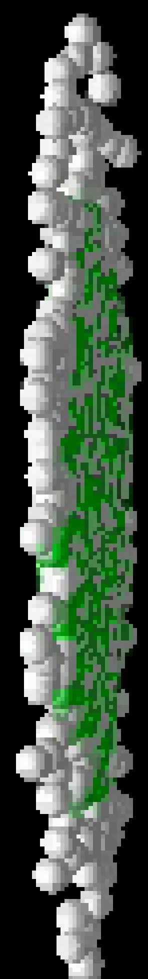


$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{E}{mc^2}$$

Objects with v~c appear "contracted"

At RHIC, we accelerate gold ions to 99.995% of the speed of light -- a ~100x compression!

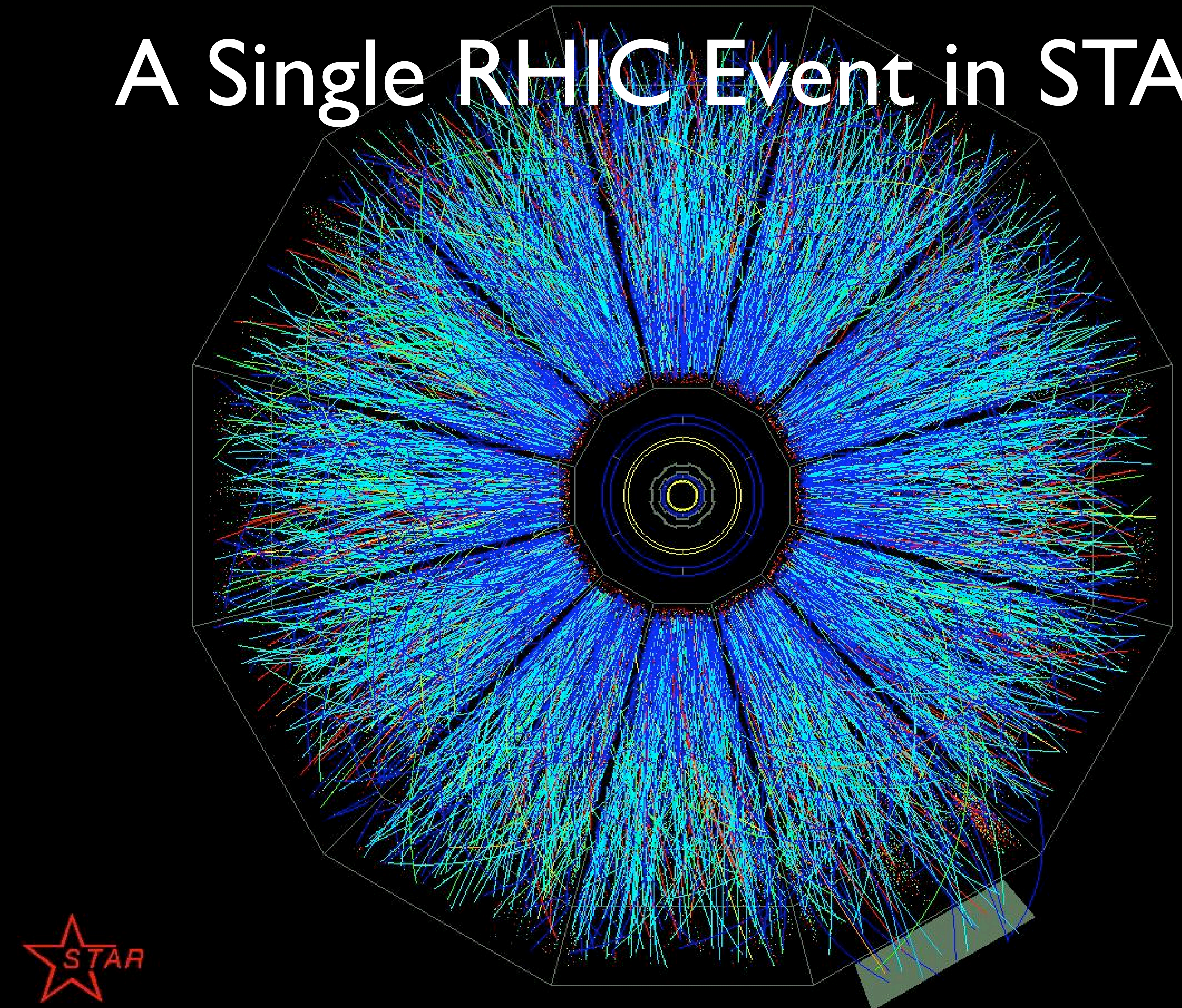
http://www.ccd.bnl.gov/visualization/gallery/au_on_au/



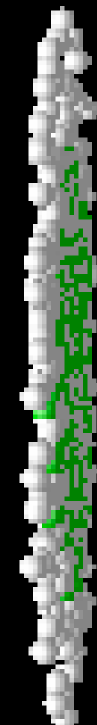
$$E = \gamma m c^2$$

We then use $E=mc^2$ as a tool - colliding nuclei at high energy makes thousands of new degrees of freedom, possibly creating a Quark-Gluon Plasma

A Single RHIC Event in STAR



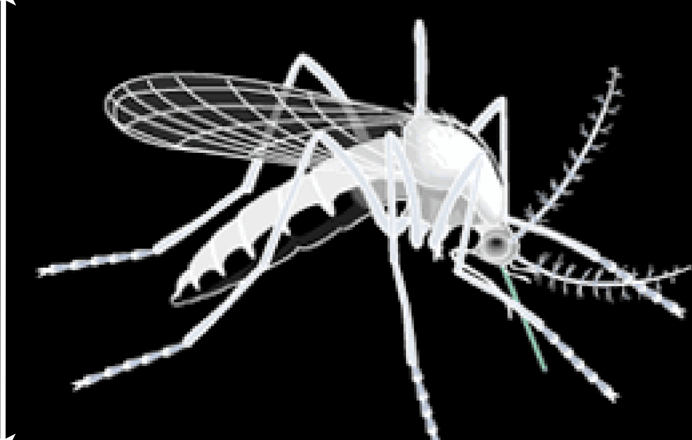
$O(10^{-15})$ m



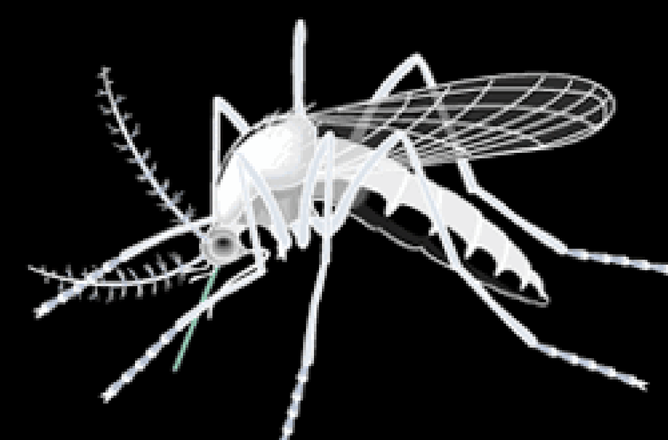
How much energy in each collision?

$$1.6 \times 10^{-19} \frac{J}{eV} \times 197 \times 200 GeV \sim 6 \mu J$$

$O(10^{-3})$m



Consider two mosquitos colliding...



$$2 \times \frac{1}{2} m v^2 = (2.5 mg) \times (2.5 km/h)^2 = 1.2 \mu J$$

A Single Event @ STAR

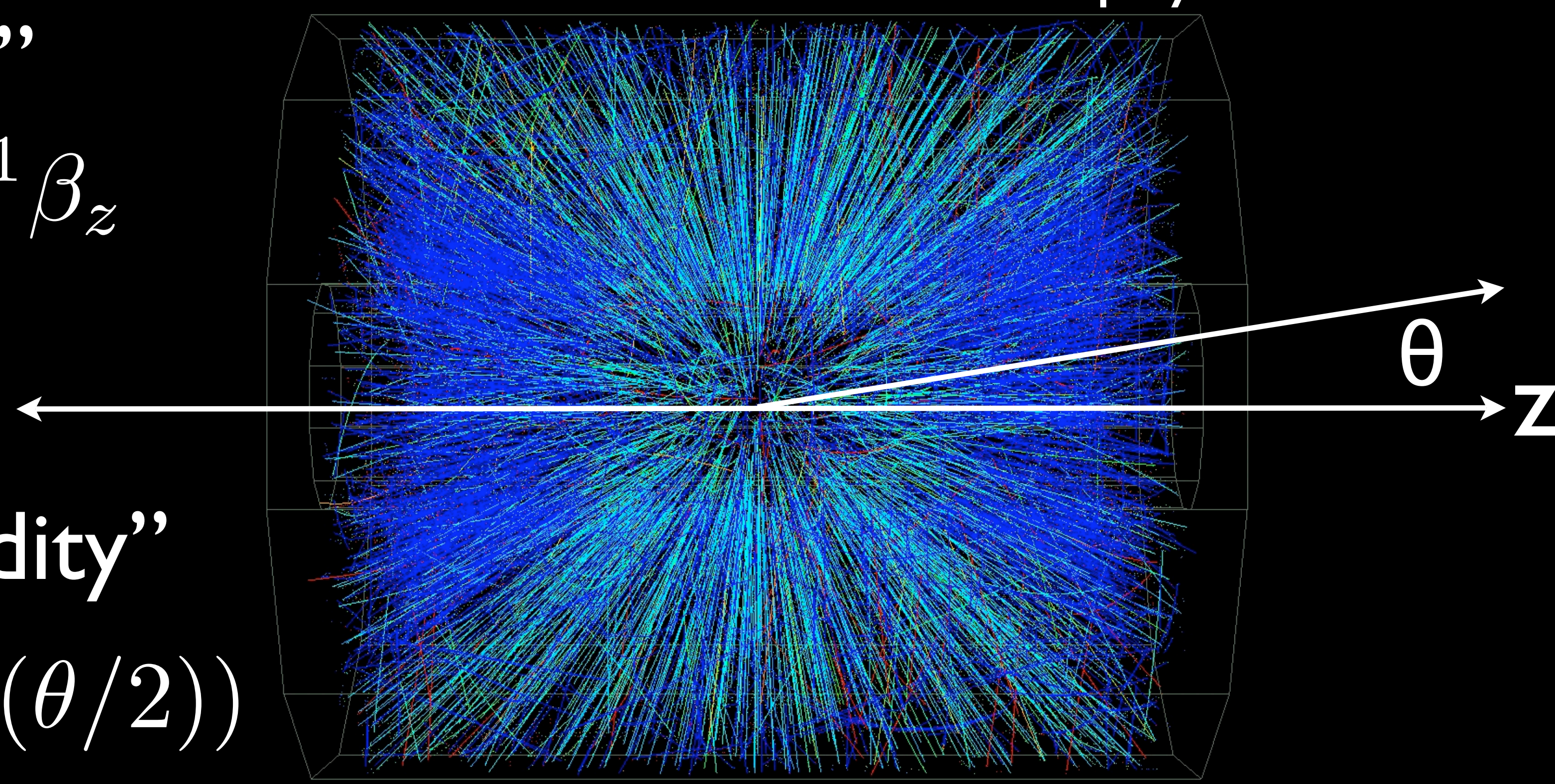
“Rapidity”

$$y = tanh^{-1}\beta_z$$

“Pseudorapidity”

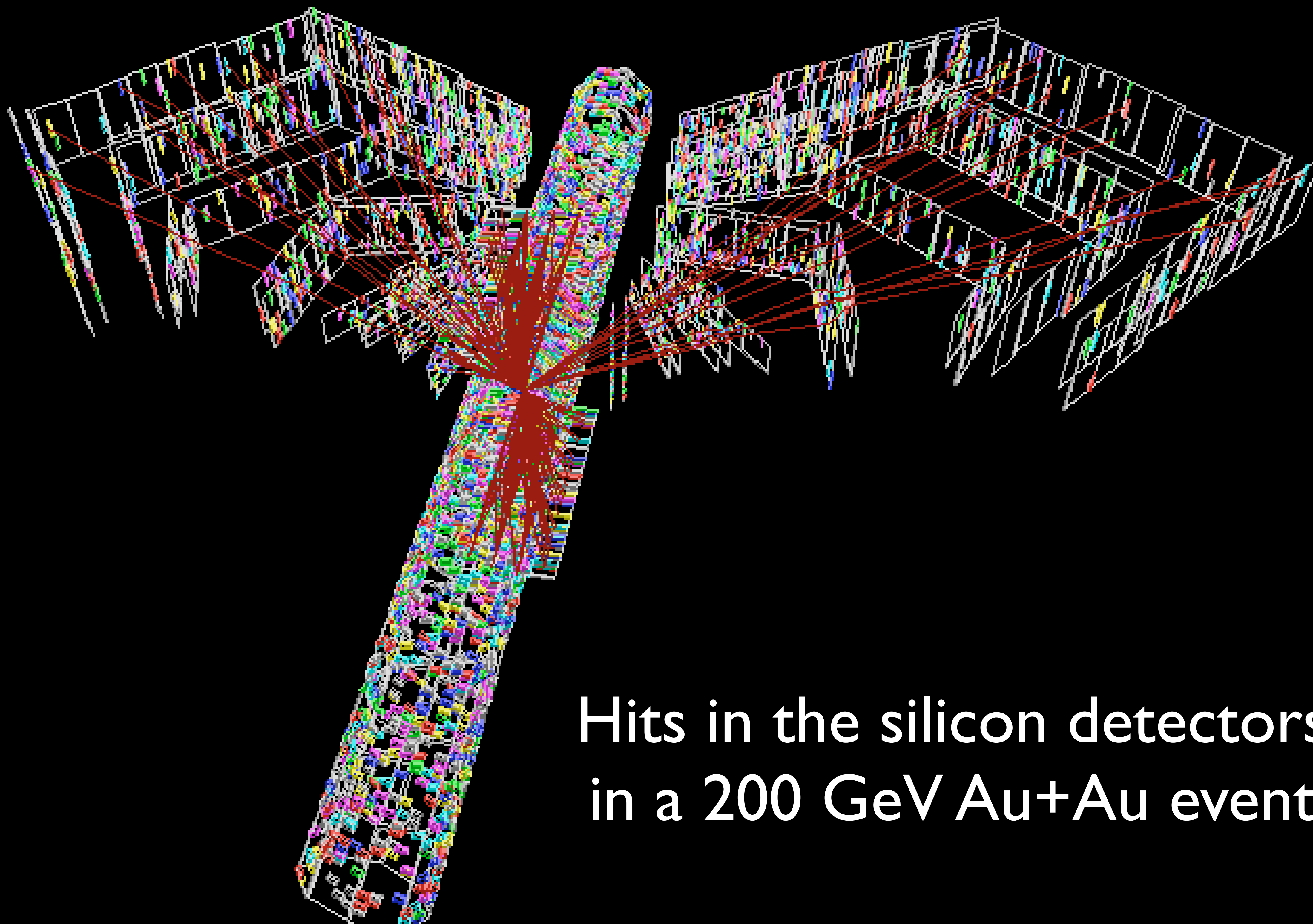
$$\eta = -\log(\tan(\theta/2))$$

STAR Event Display



Let’s “unwrap” a typical RHIC event in a “lego plot” (η(θ) and ϕ)

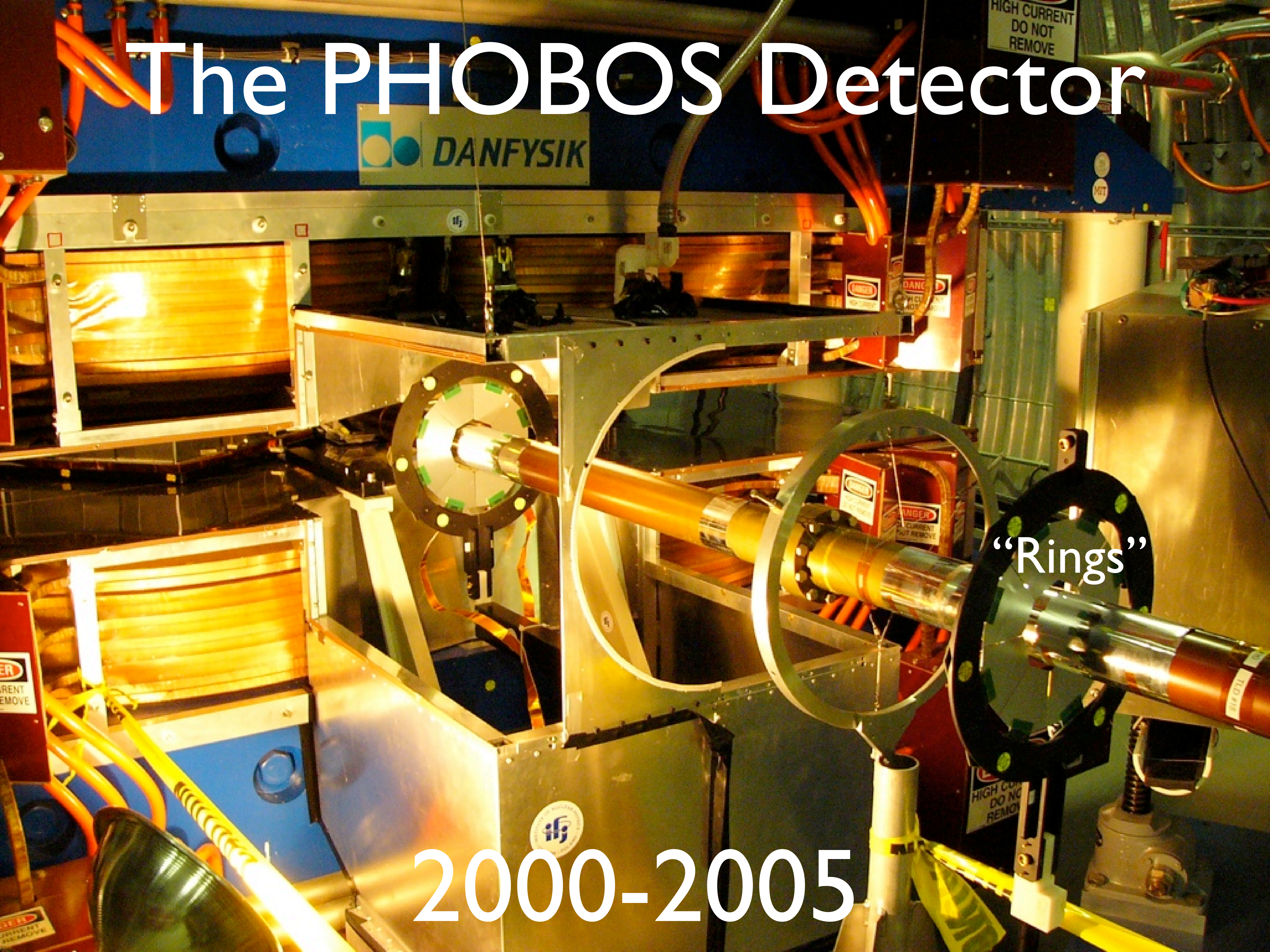
A Single Event in PHOBOS



Hits in the silicon detectors in a 200 GeV Au+Au event

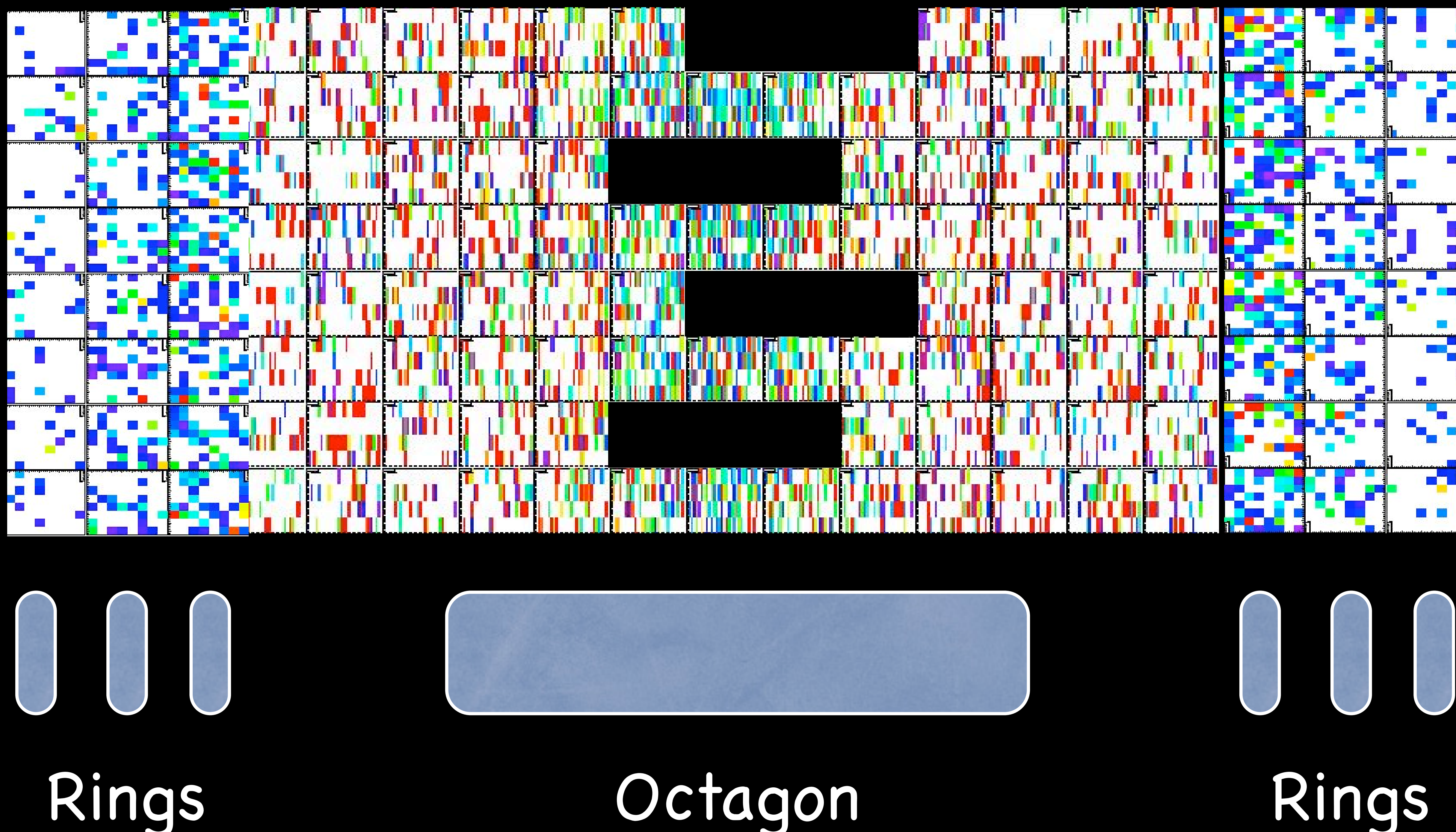
“Octagon”

The PHOBOS Detector



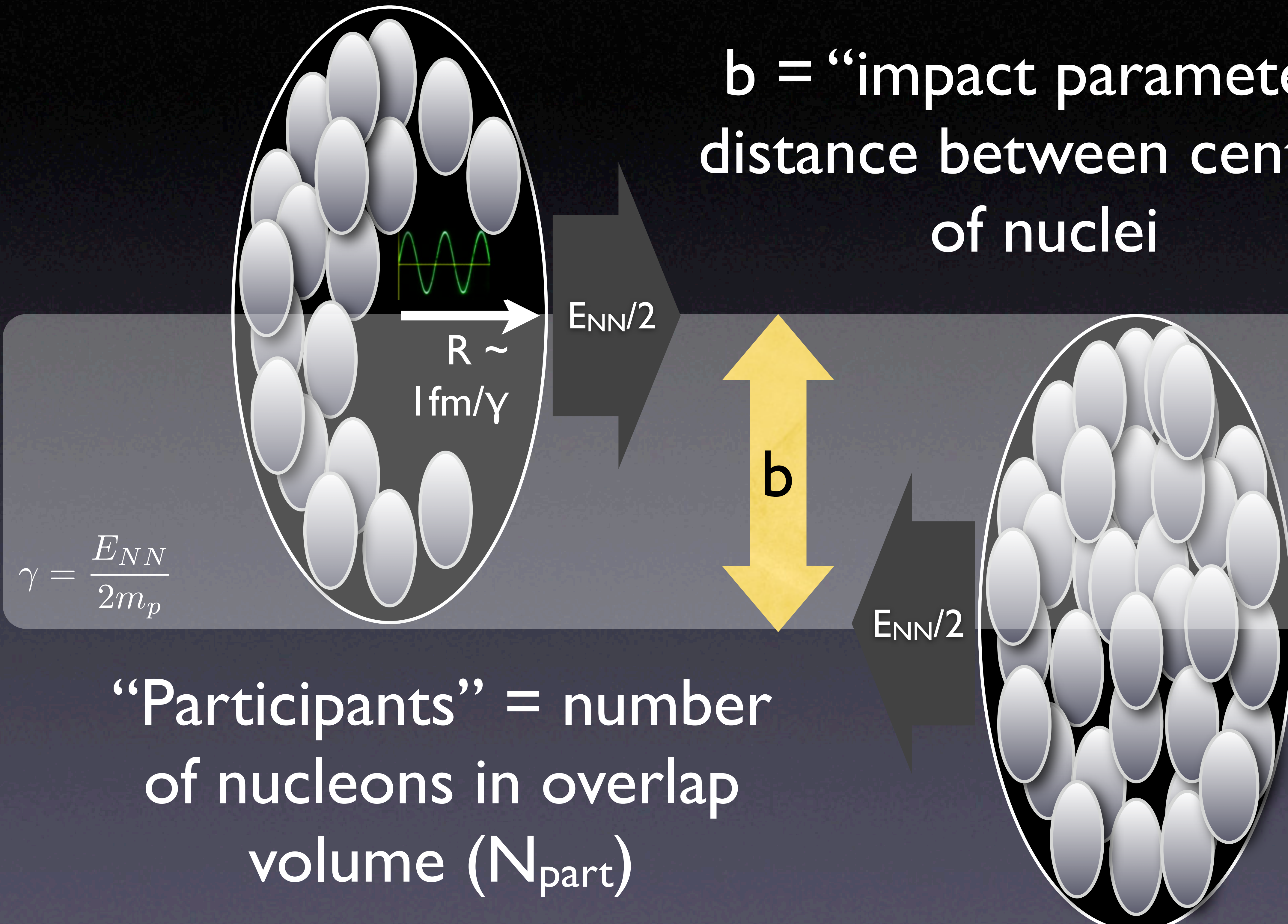
2000-2005

A Single Event @ PHOBOS

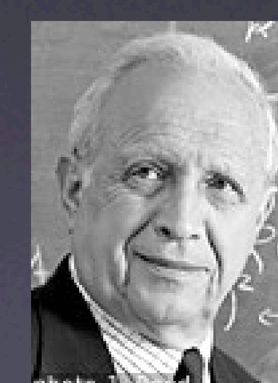


Collision Variables

b = “impact parameter” distance between centers of nuclei



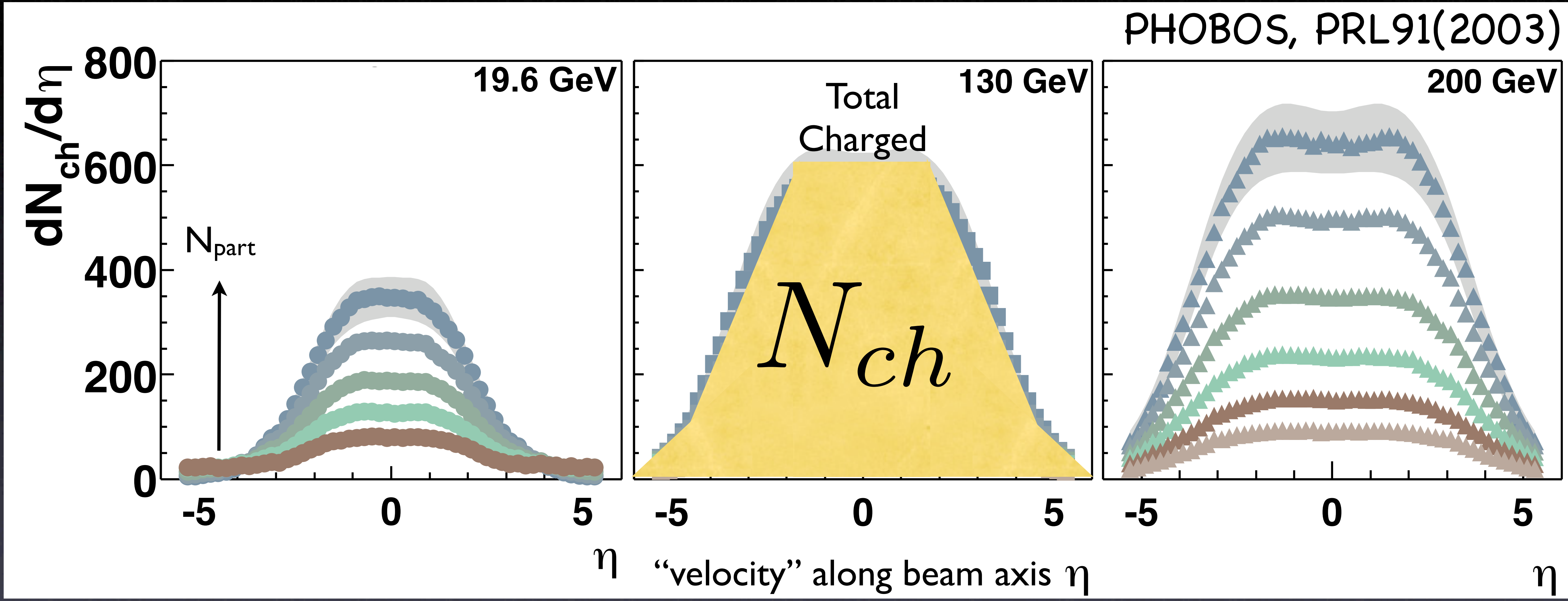
“Participants” = number of nucleons in overlap volume (N_{part})



Glauber

And of course, the collision energy of E_{NN}=200 GeV!

Angular Distributions & N_{ch}



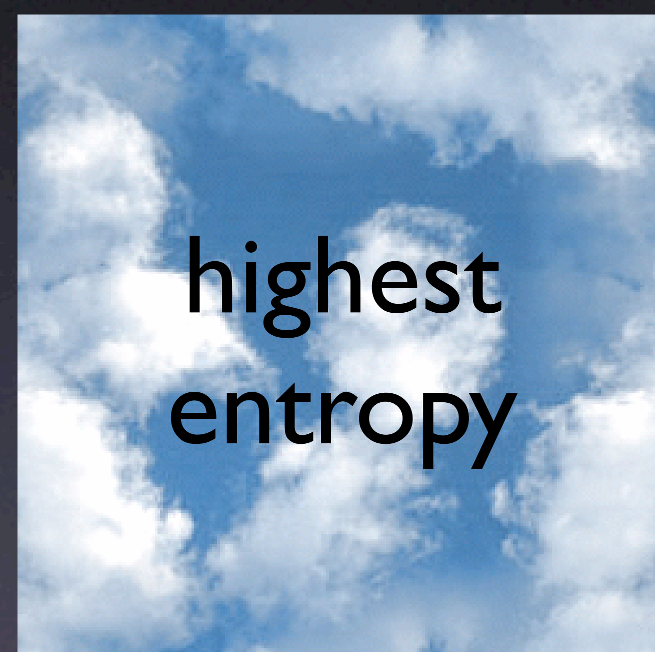
<u>Angle</u> tells us about velocity of particles along beam axis.

Most produced particles are relatively slow.

$E=mc^2$: Trade off of kinetic energy for matter

Entropy & Thermalization

Entropy (in one definition) reflects the number of degrees of freedom available to a system when it "thermalizes", i.e. erases all information about its initial state by randomizing the motion of the constituents



$$S = \frac{\Delta Q}{T}$$

Do collisions at RHIC thermalize? If so, we may be able to learn about the relevant constituents by studying its entropy!

Counts "information" even with non-stable particles

Entropy & Multiplicity

$$S = \frac{\Delta Q}{T}$$

Total amount of energy added as "heat"

Average energy per relevant degree of freedom

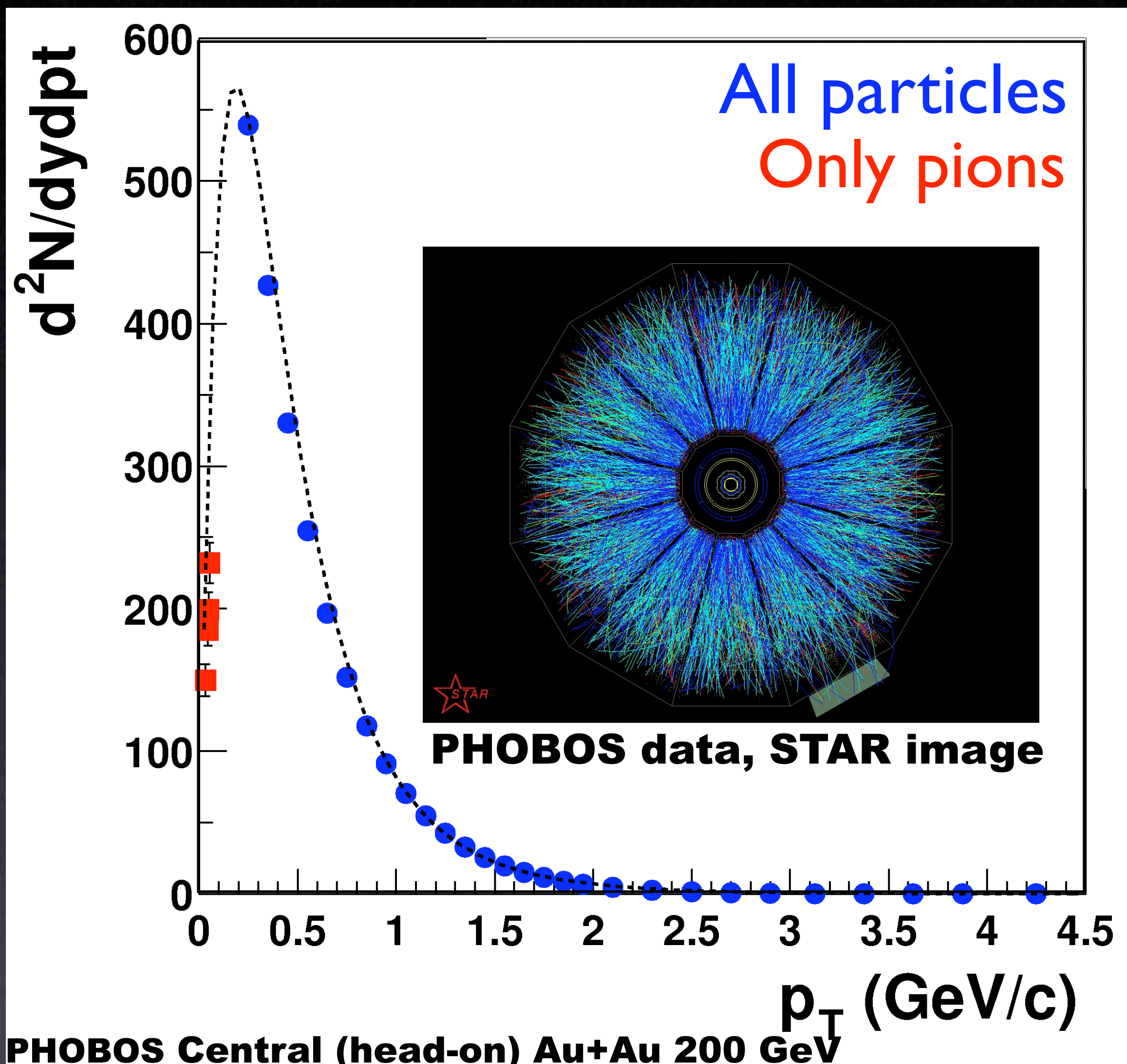
$$\propto N_{DOF} \propto N_{tot}$$

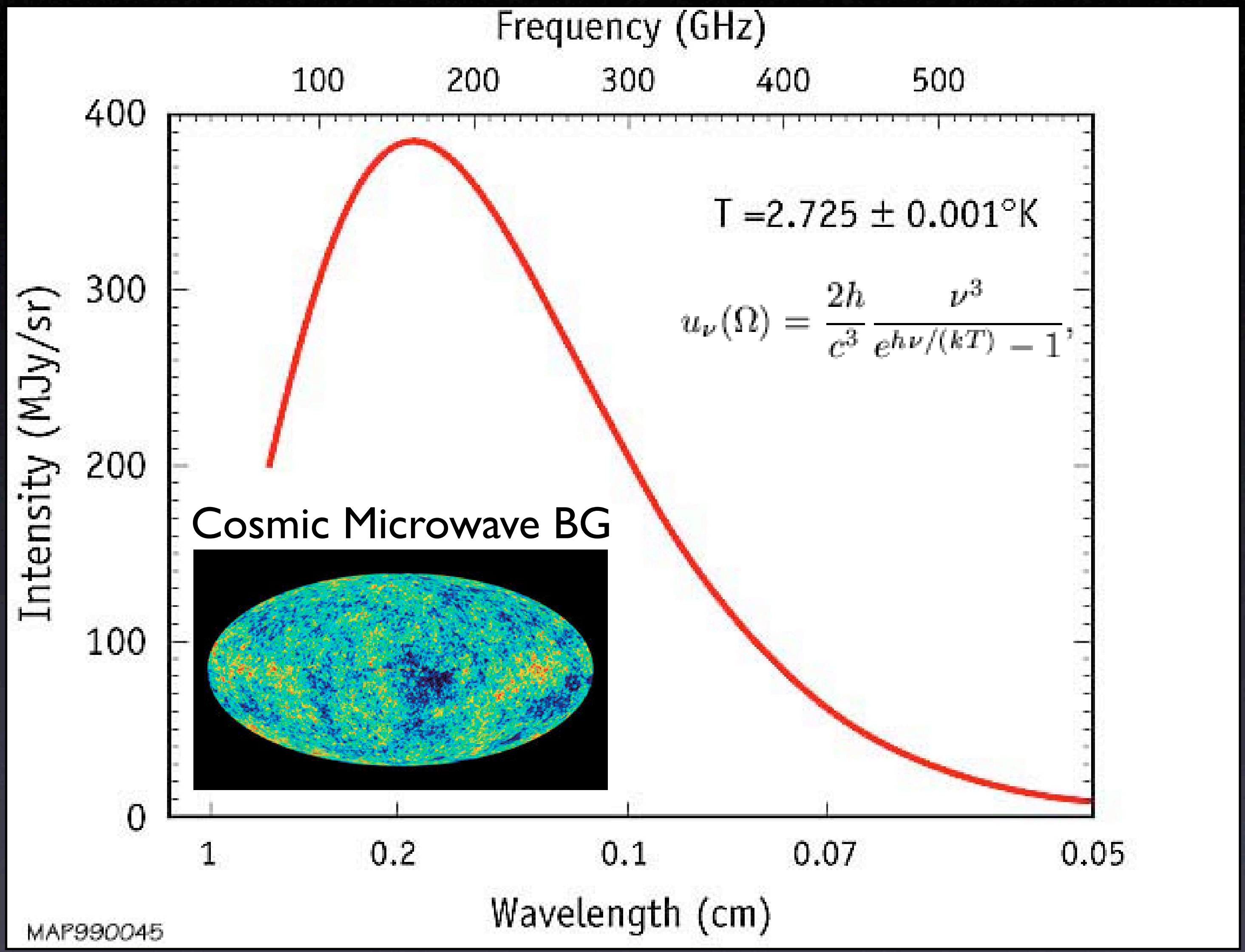
For entropy, <u>everything</u> "counts"...

The Final State @ RHIC

Can we see thermalization in the final state?

Strong Blackbody





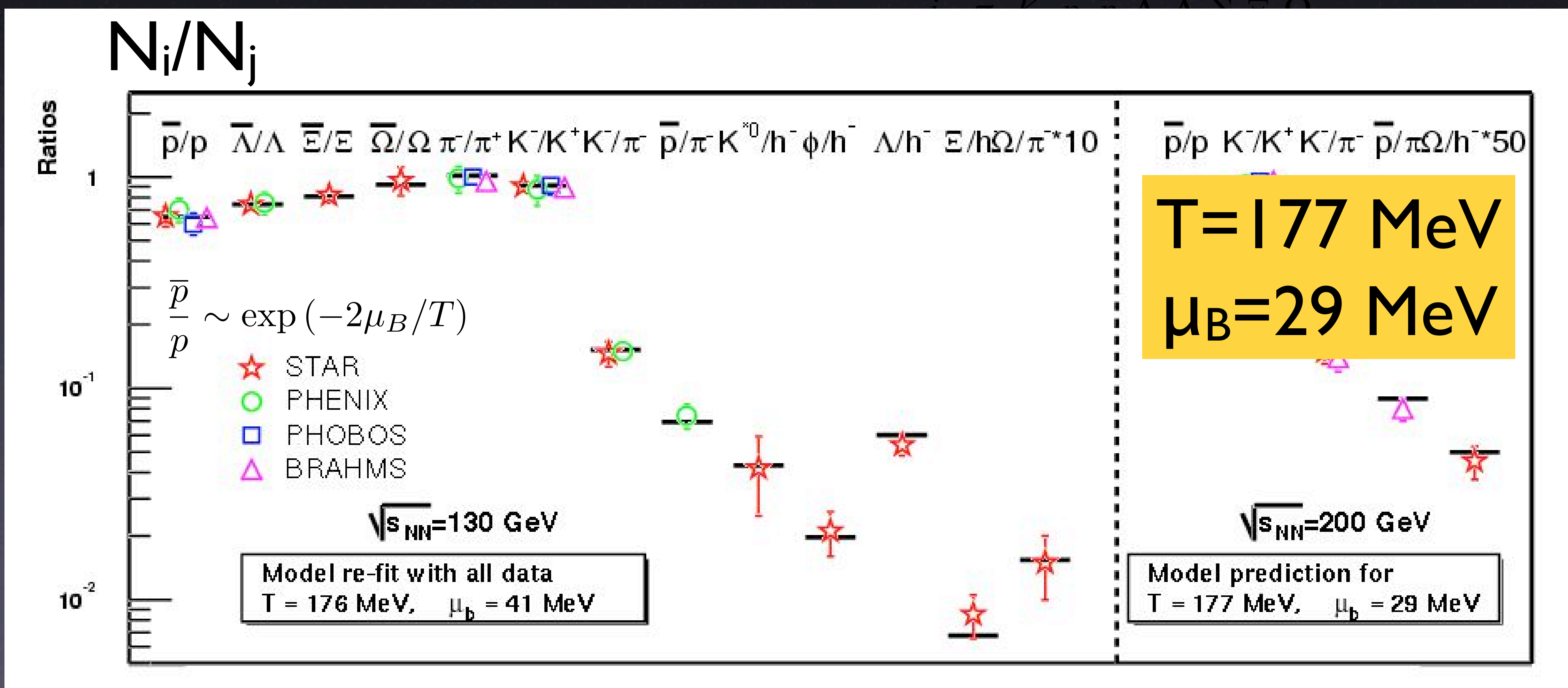
The spectrum of particles emerging from the collisions seems to have a blackbody shape, but with hadrons instead of photons

Particle Ratios

T	Chemical freezeout temperature
μ_B	Baryochemical potential (when you have more matter than antimatter!)

$$N_i \propto V \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B)/T} \pm 1}$$

Blackbody spectrum



Braun-Munzinger, Magestro, Stachel (2001)

The Temperature at RHIC

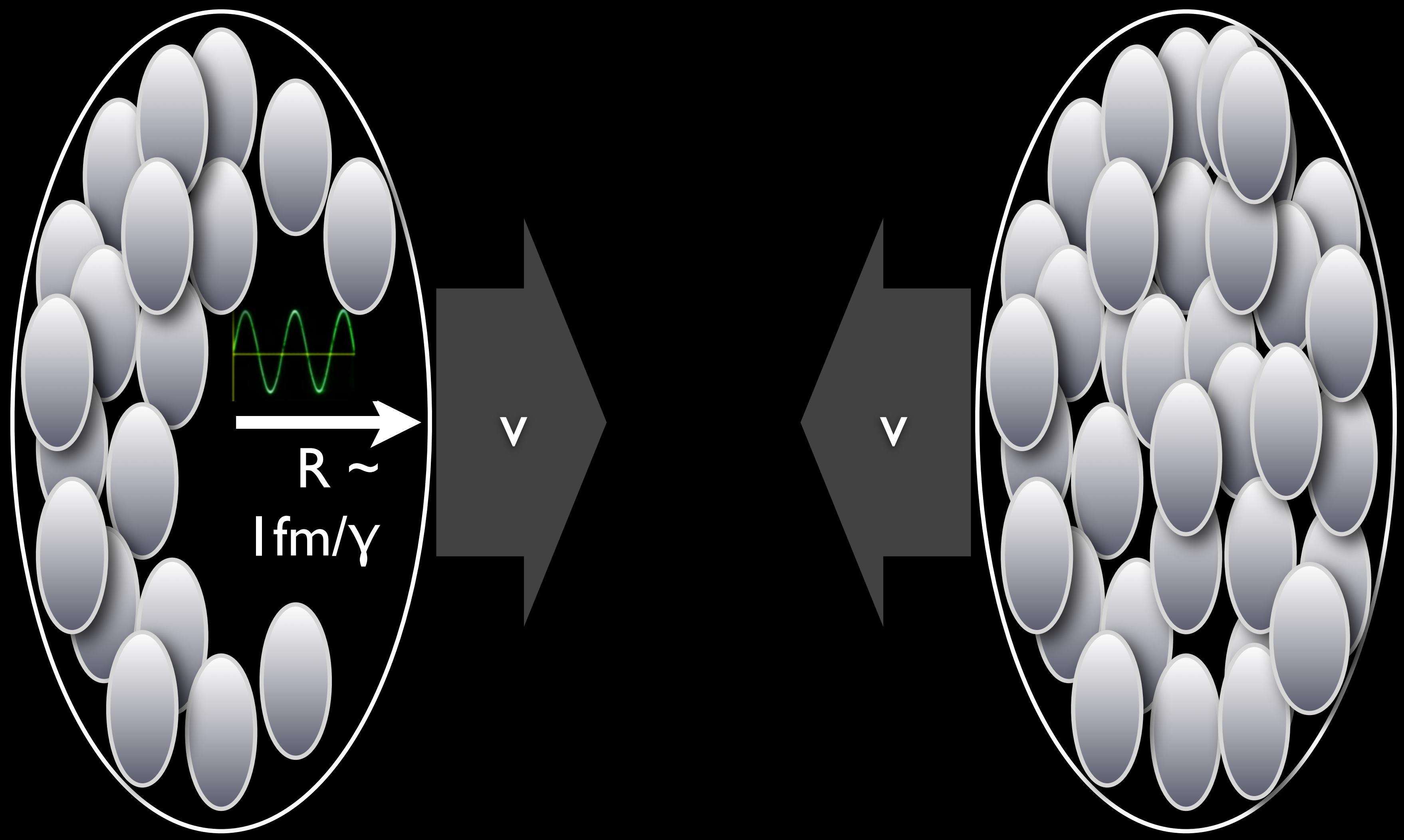
$k_B T = 177$ MeV

This is ~2×10^{12} degrees K

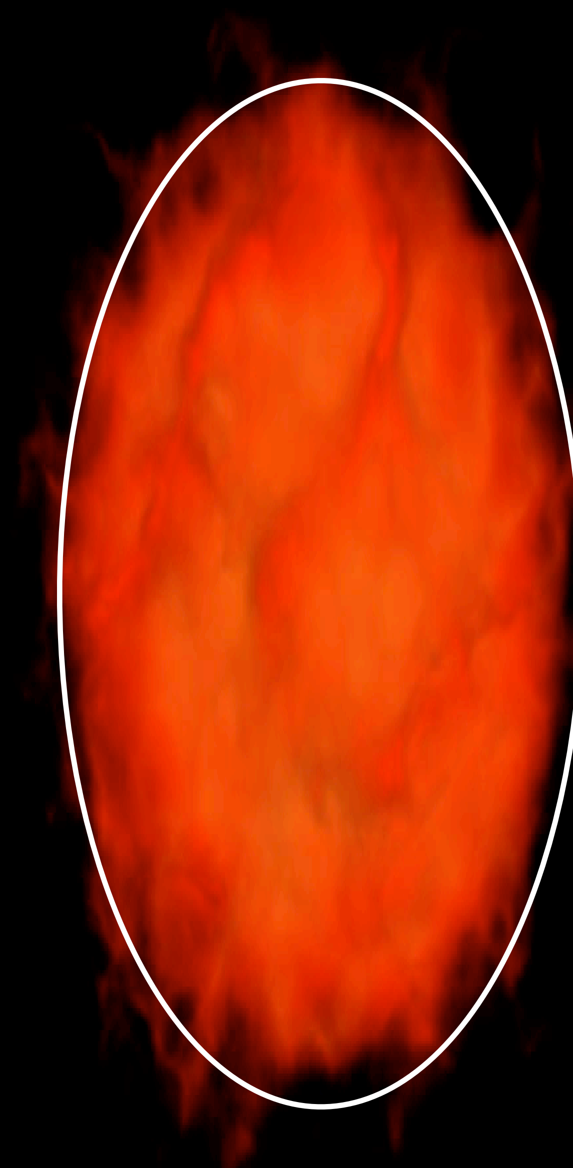
This is, in some sense, the
"final temperature"
of a RHIC collision, when
it "freezes" into hadrons

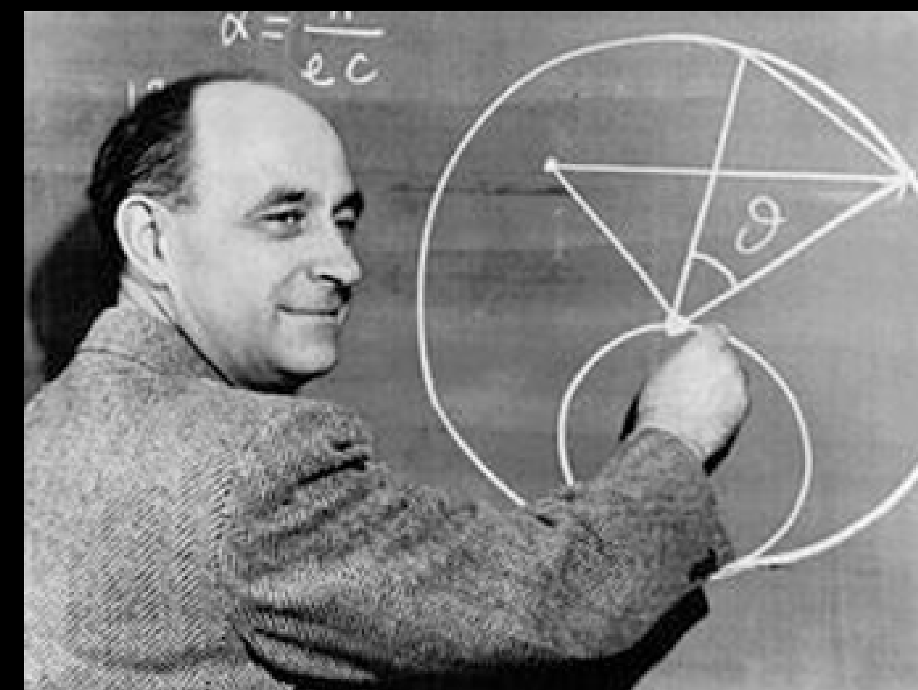
The earlier stages must have
been <u>*much*</u> hotter!

A Simple Model for Entropy

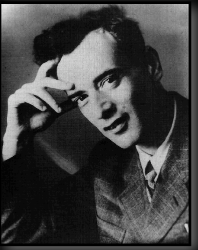
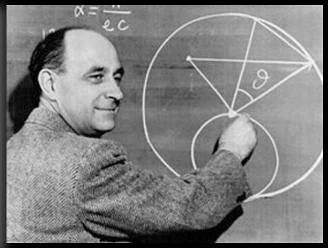


A Simple Model for Entropy





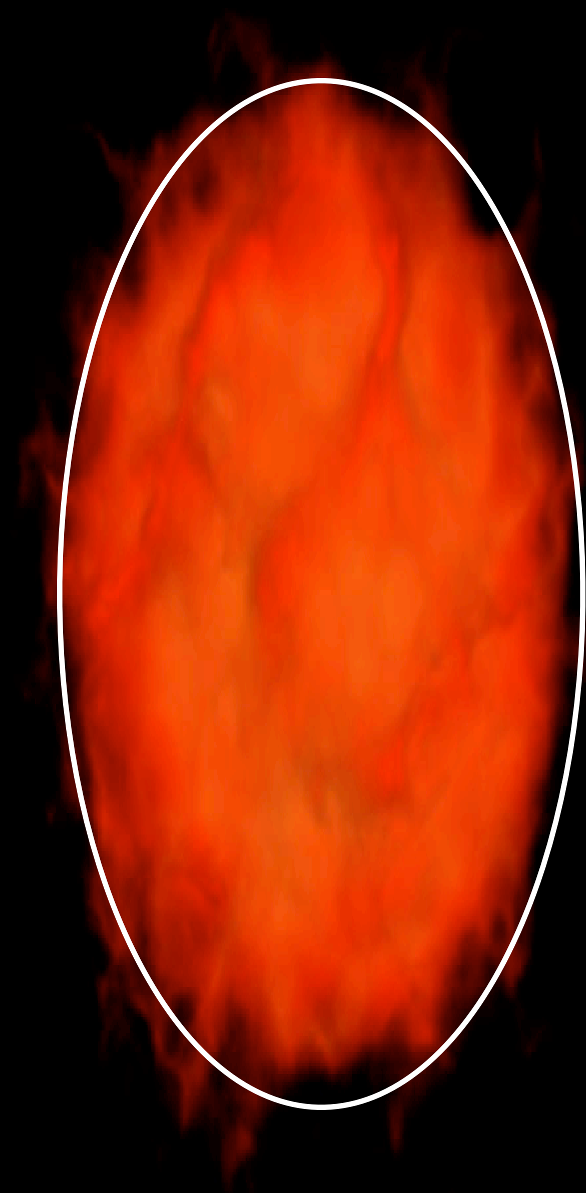
What if the system thermalized immediately,
in the Lorentz-contracted volume?
What would the entropy be?



Fermi-Landau Model

$$E = A \times E_{NN}$$

Total Energy



$$V = \frac{A \times V_0}{E_{NN}/2m_N}$$

Total Volume

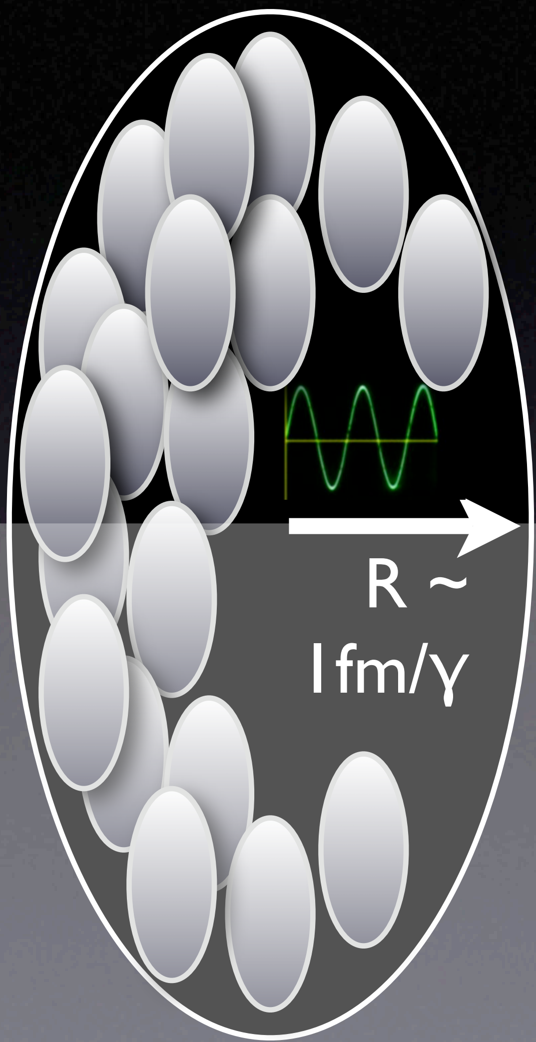
$$\epsilon = \frac{E_{NN}^2}{2m_N V_0}$$

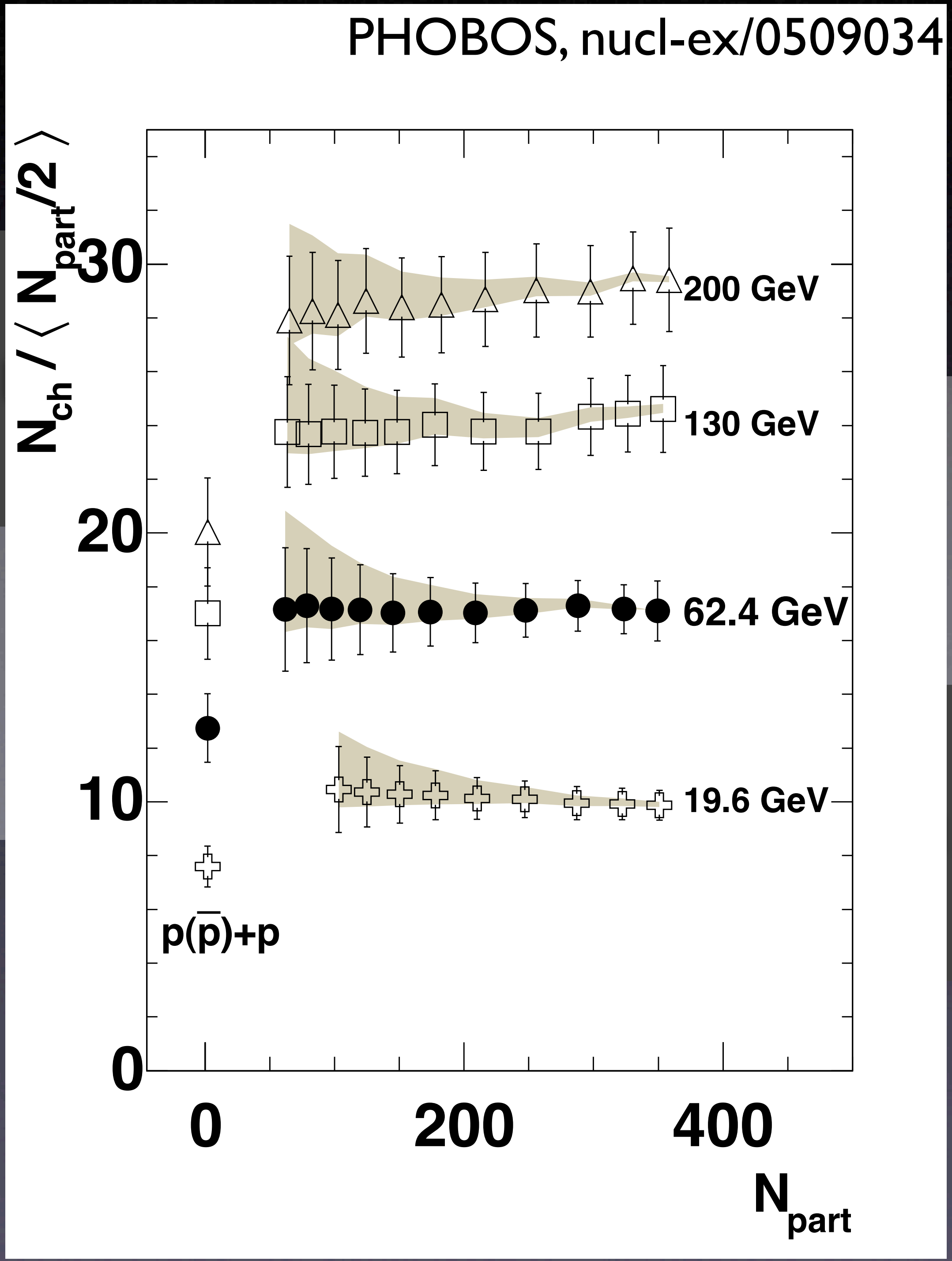
Energy Density E/V
(>3 TeV/fm^3 @ RHIC!)

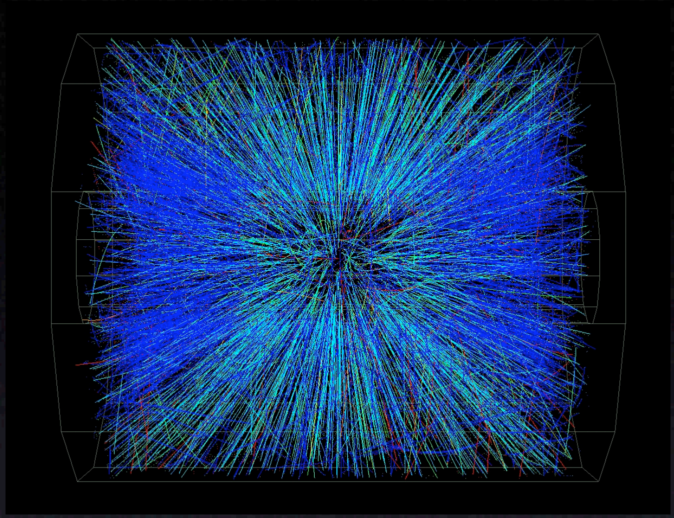
$$s \propto \epsilon^{3/4}$$

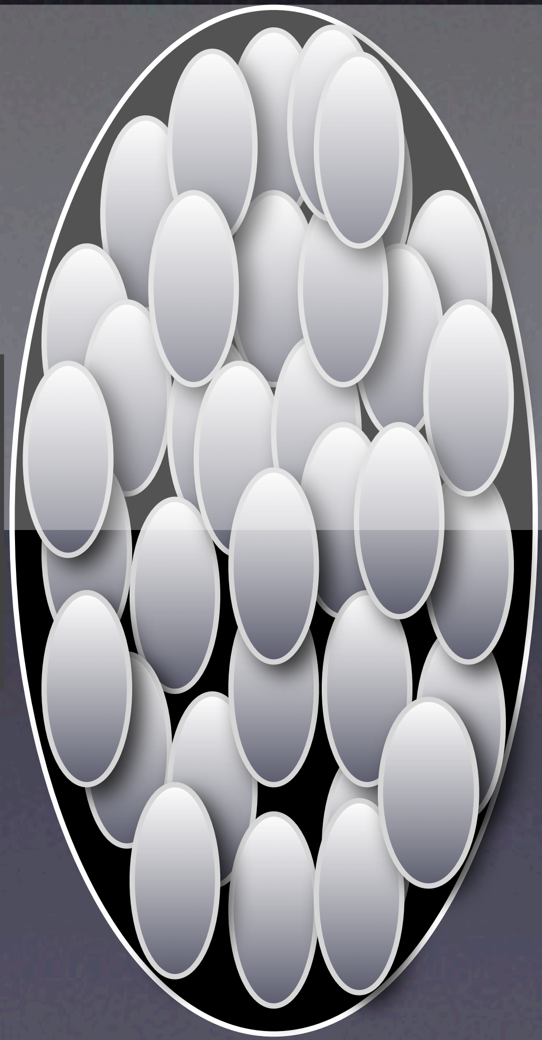
$$S = sV \propto N_{part} E_{NN}^{1/2}$$

N_{ch} vs. Volume





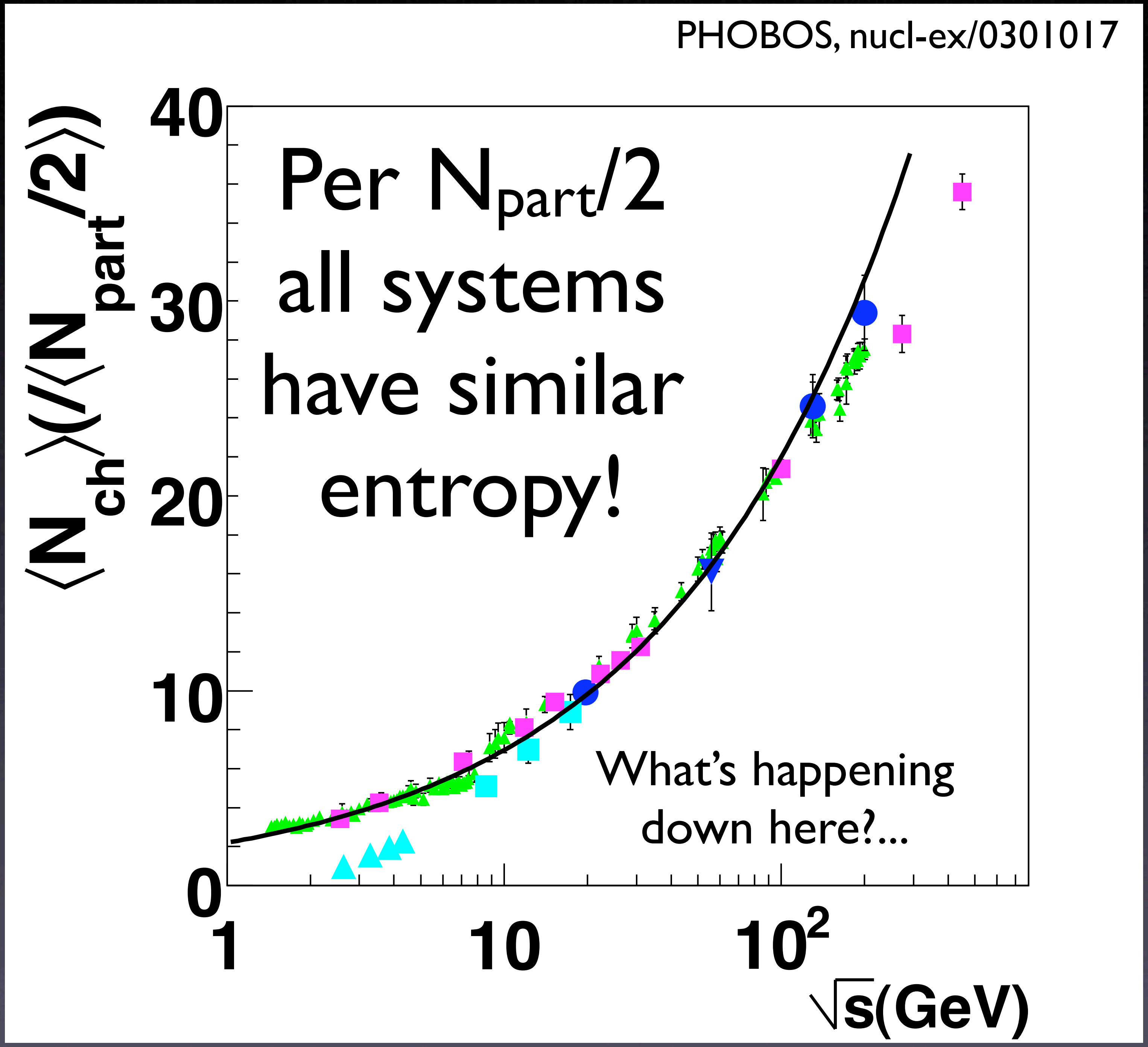




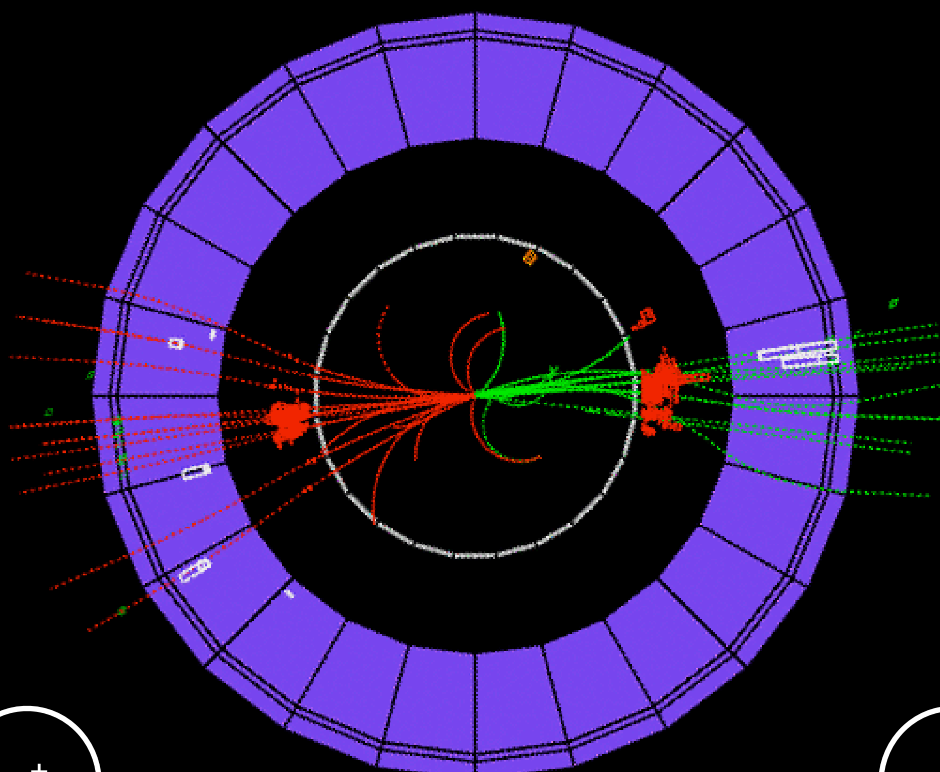
Total charged is <u>linear</u> with N_{part}

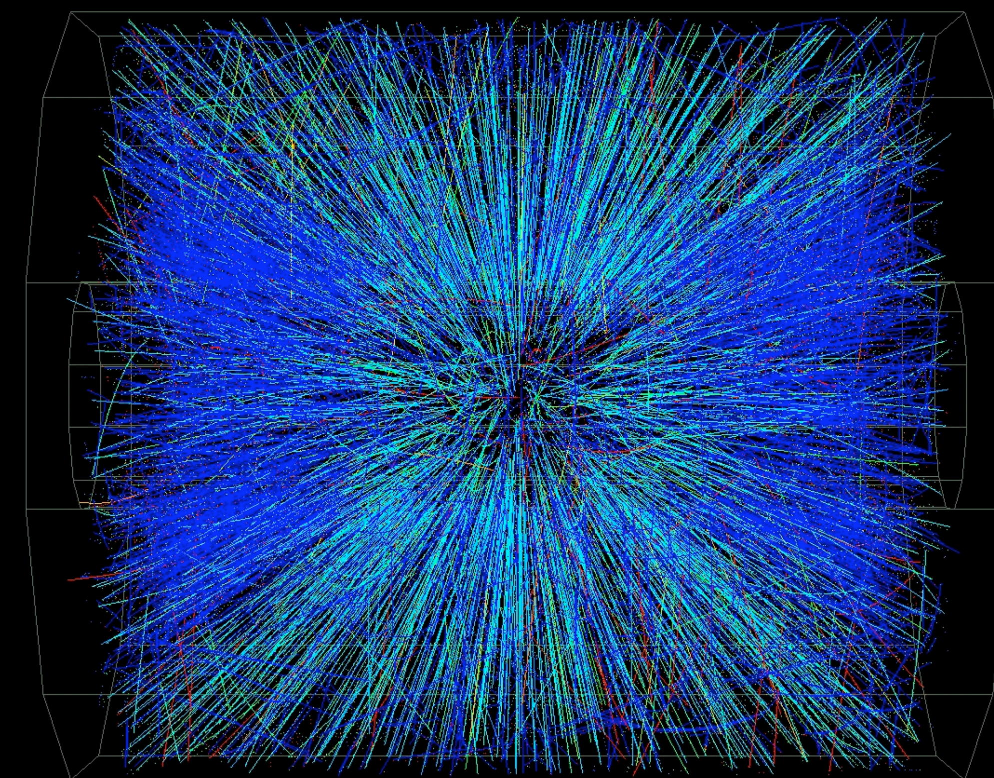
$$\frac{N_{ch}}{N_{part}/2} = f(E_{NN})$$

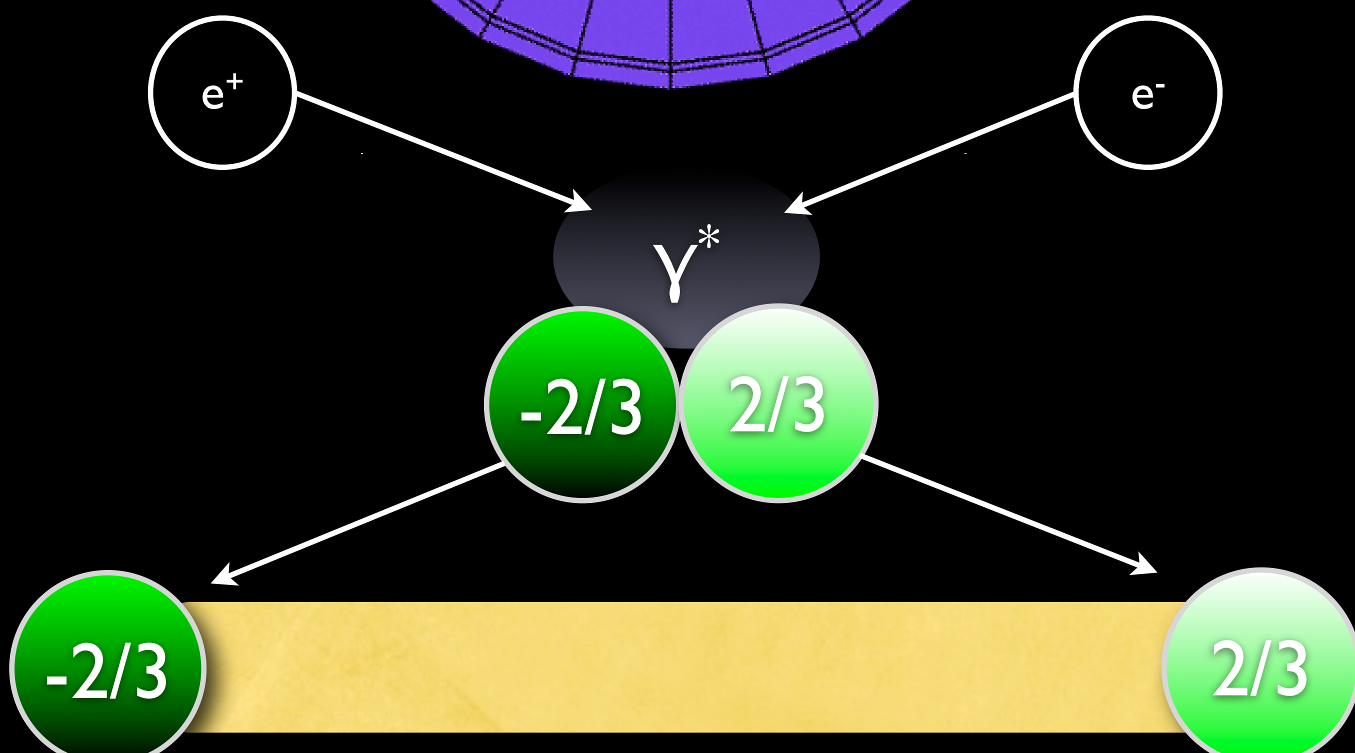
Fermi & Landau vs. Data

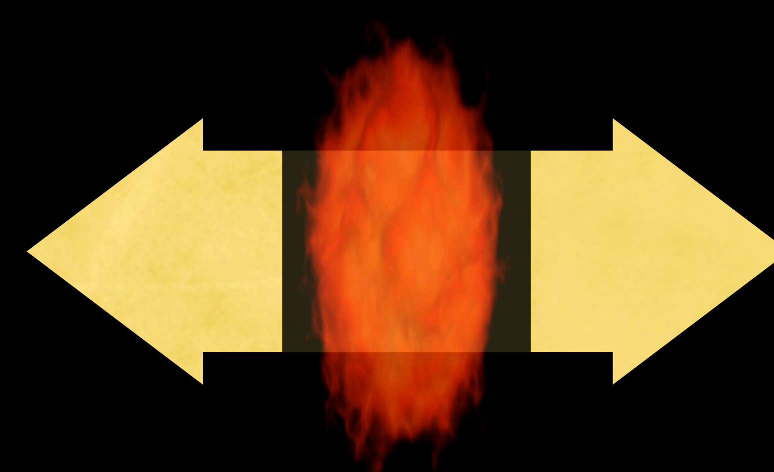


e^+e^- vs. A+A

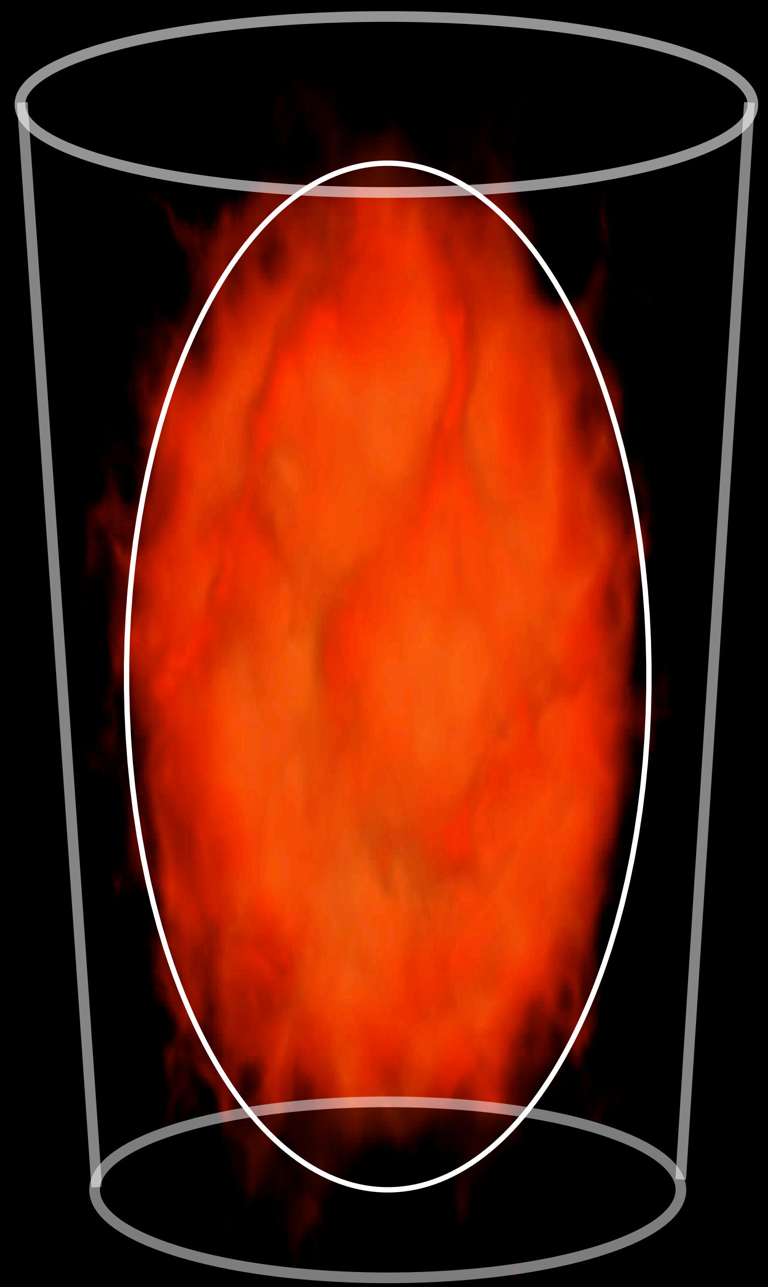






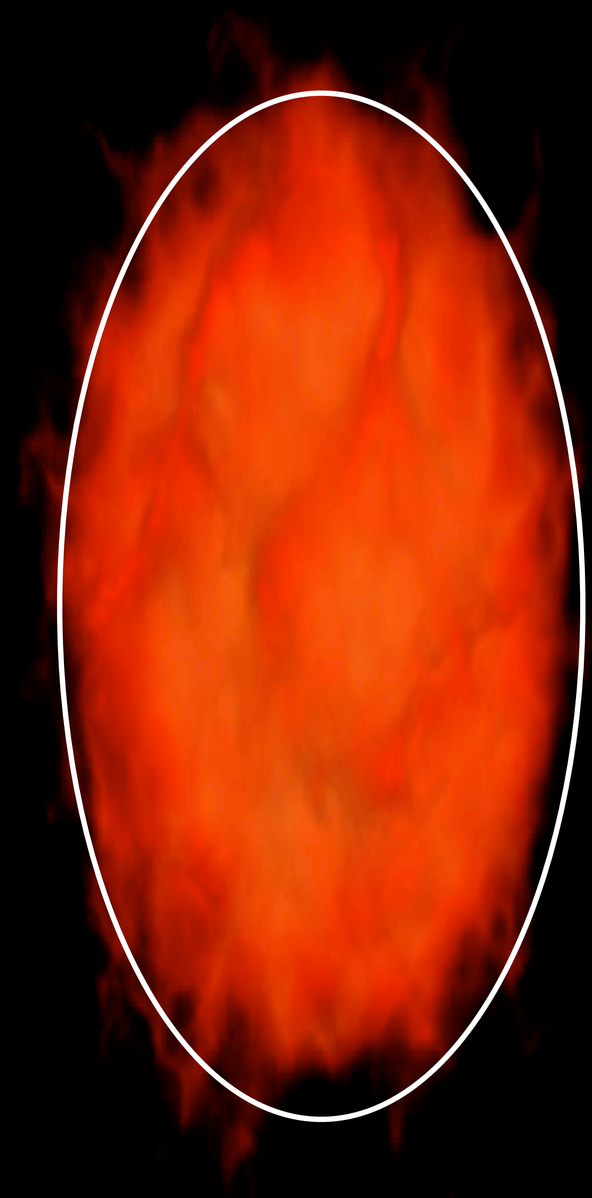


Similar multiplicity after dividing by $N_{part}/2$



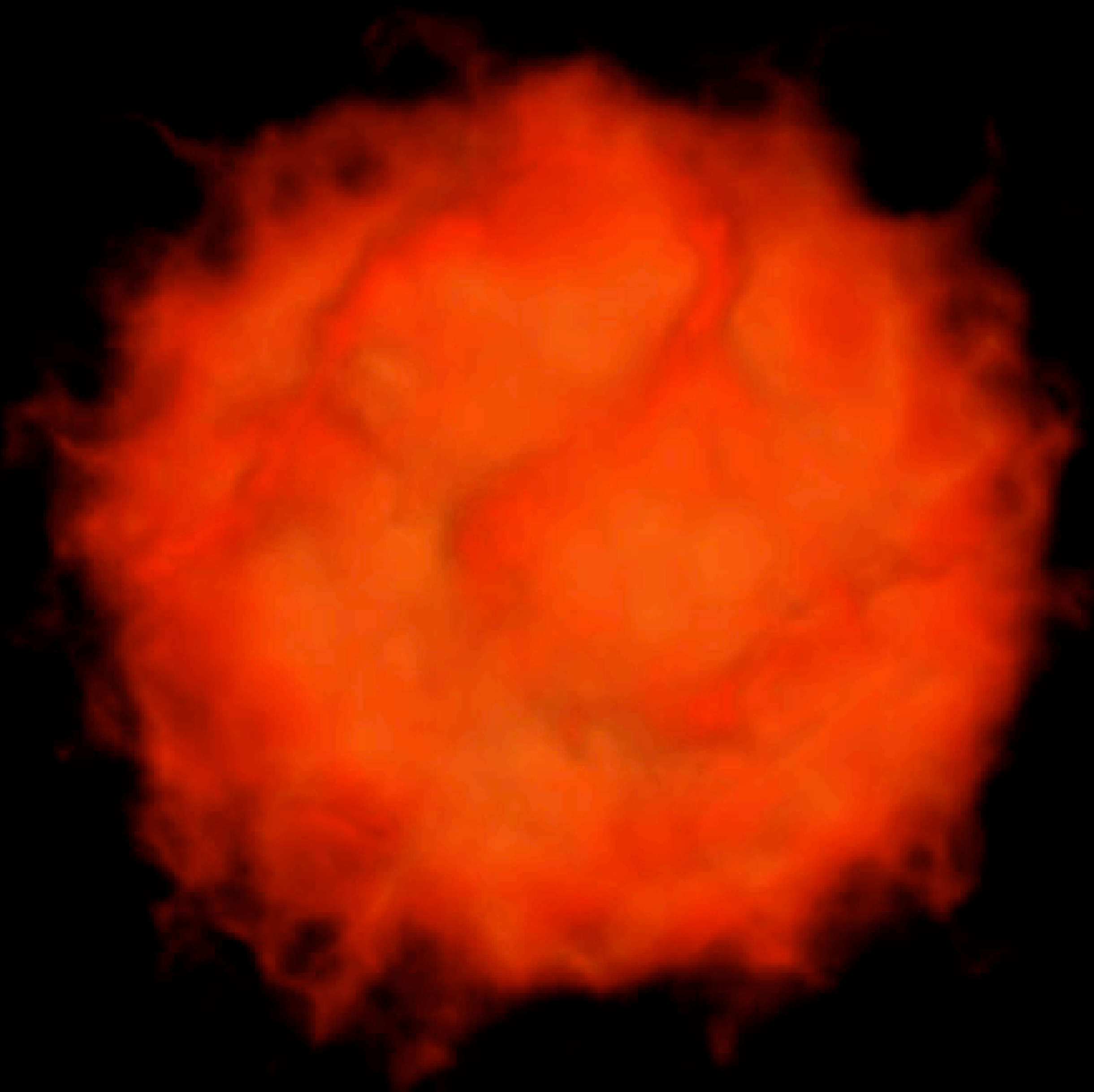
So far we've been treating the system as if it's sitting in a box (or test tube!)

Set the QGP Free!



What happens when you take the glass away?

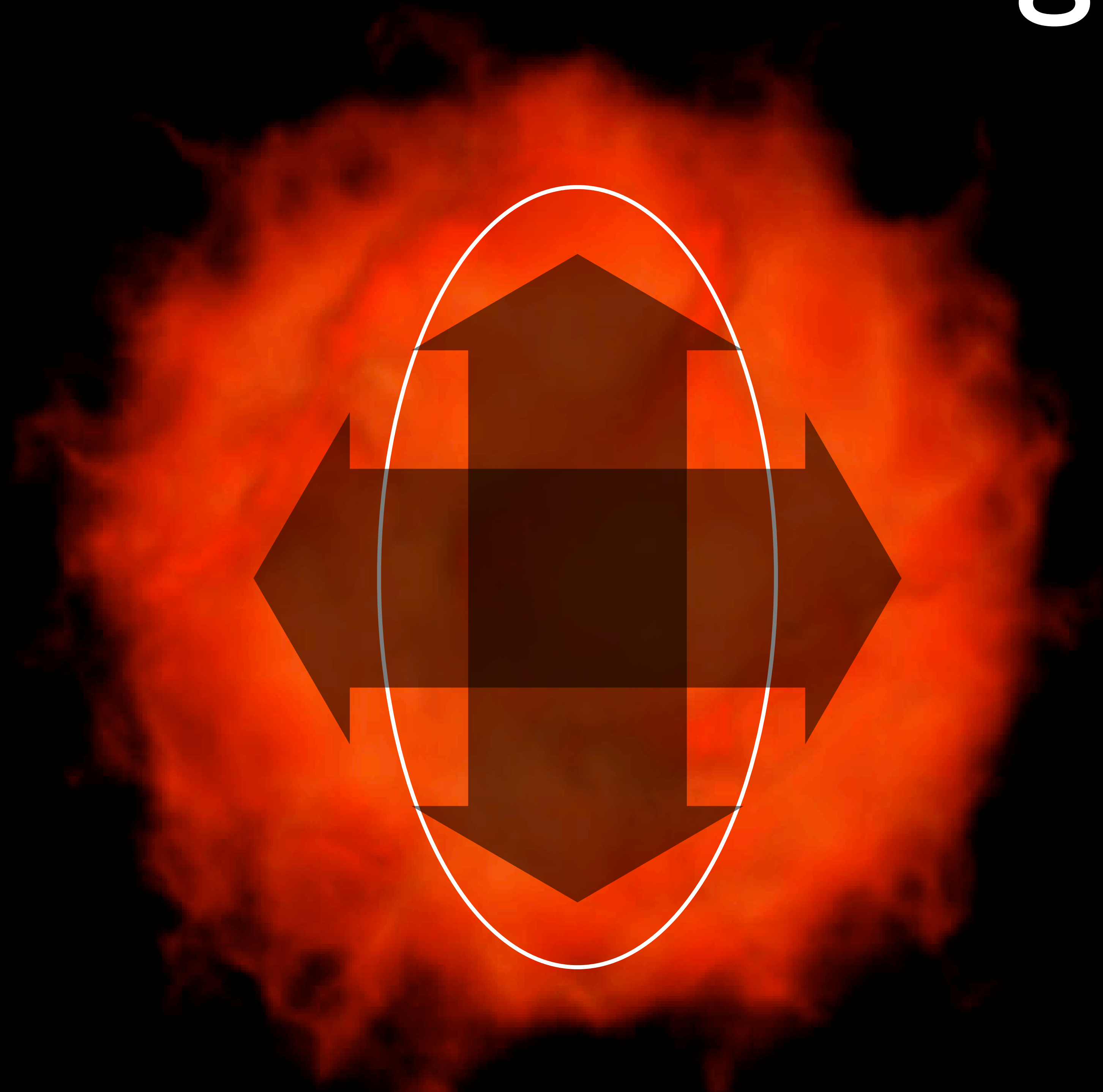
The Stuff at RHIC



Does it evaporate, like a gas?

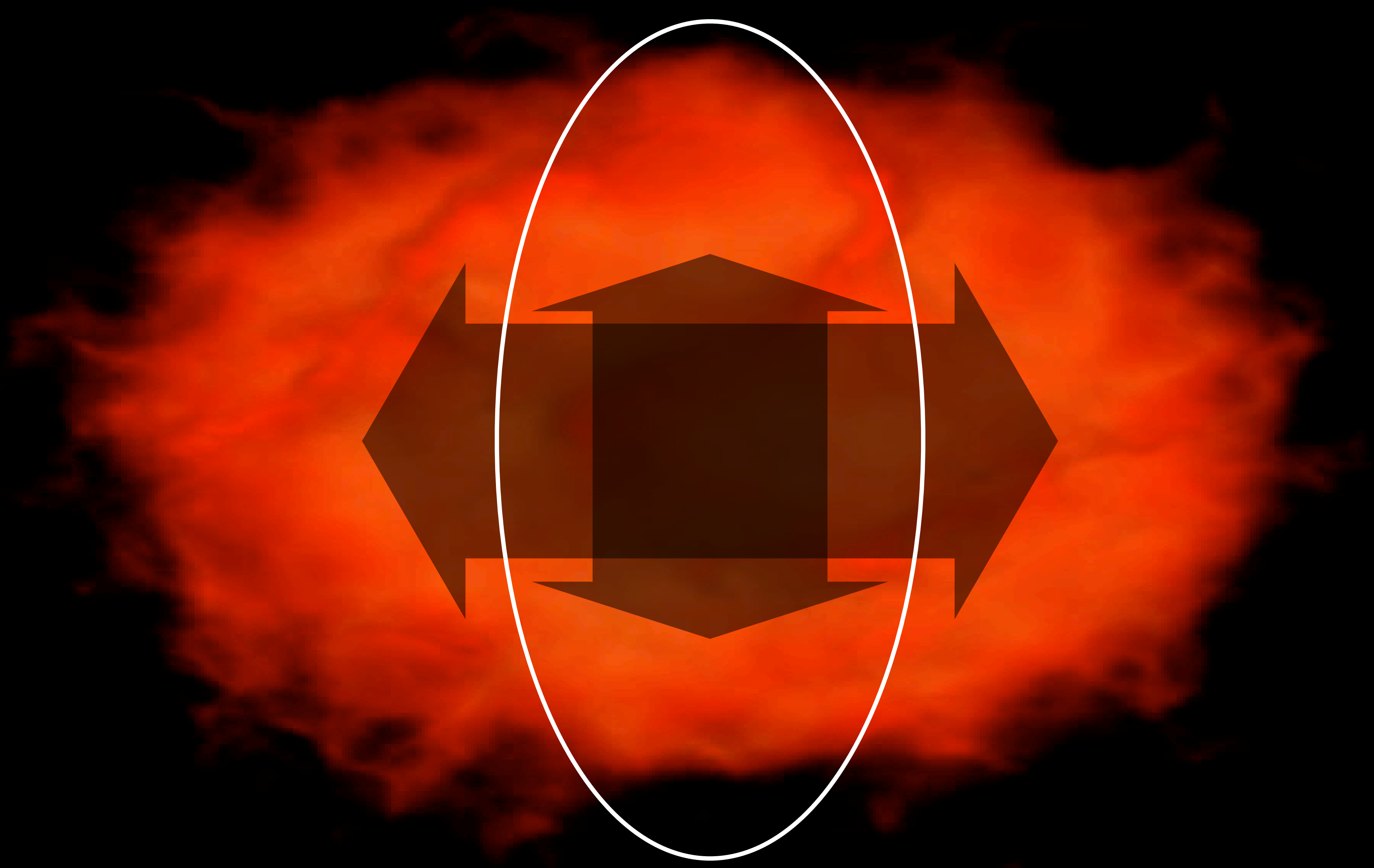
Does it flow, like a liquid?

Is the material a gas?



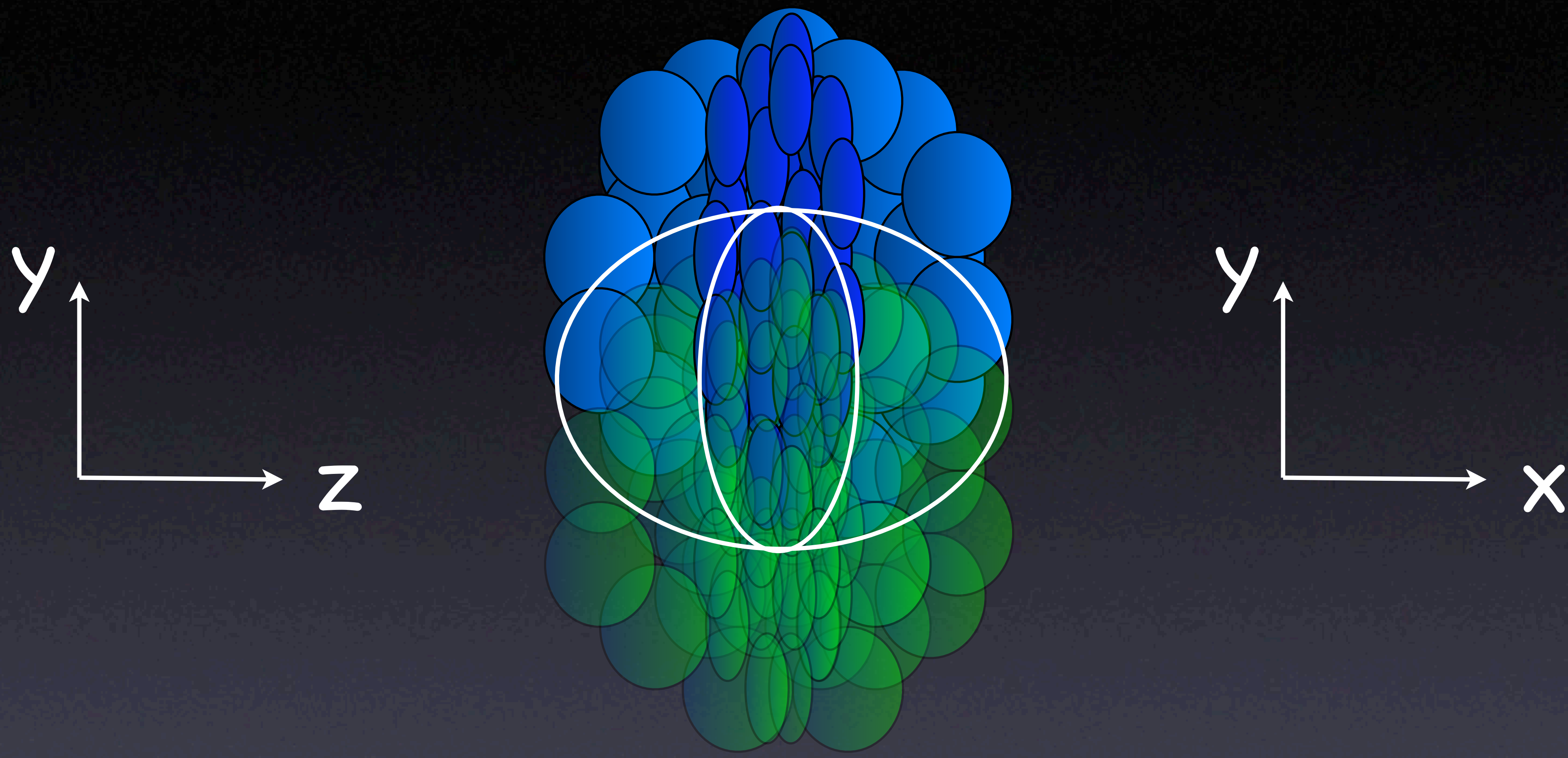
A gas just expands into whatever it can. It flows down a pipe, but just expands isotropically into space.

Is the material a liquid?



A liquid is its own container.
Its flow depends on its shape

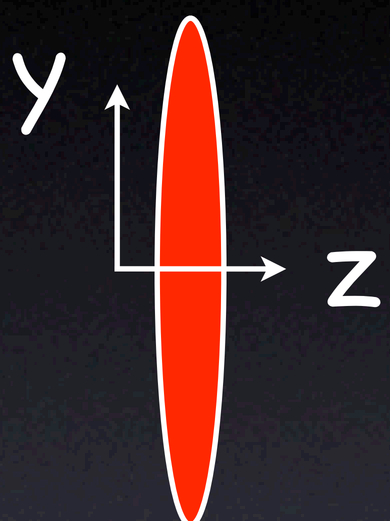
The “Shape” of Things



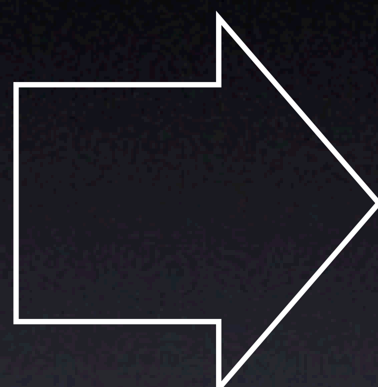
RHIC collisions have a special shape:

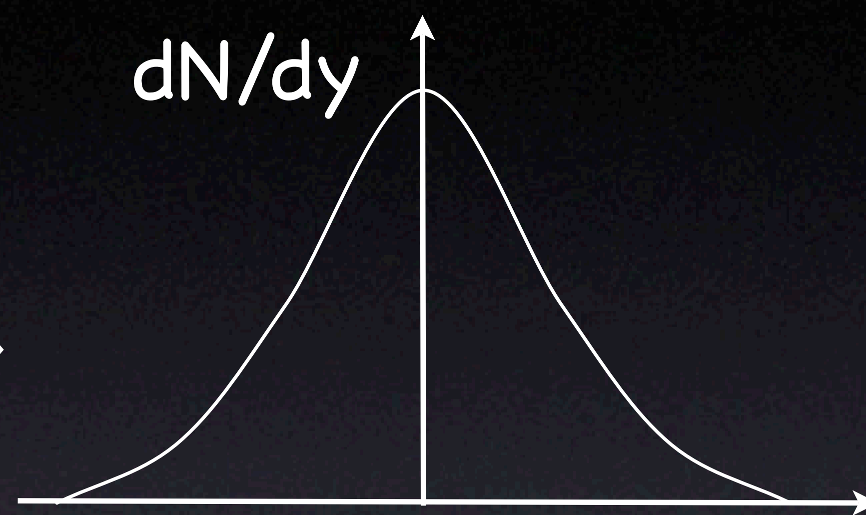
1. Compressed along the beam directions
2. Almond shaped in the “transverse” plane

Longitudinal Flow

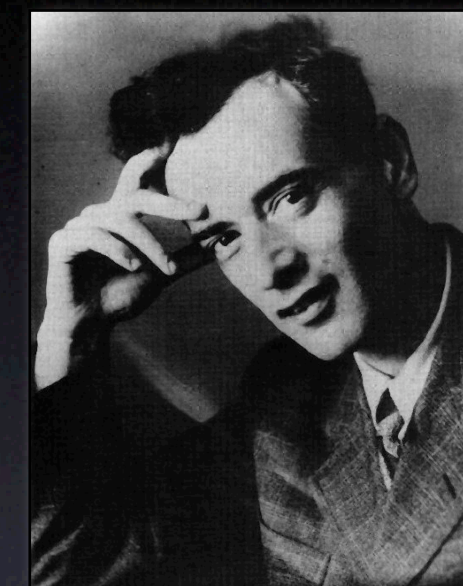


$$\Delta z \sim \frac{1}{\sqrt{s}}$$

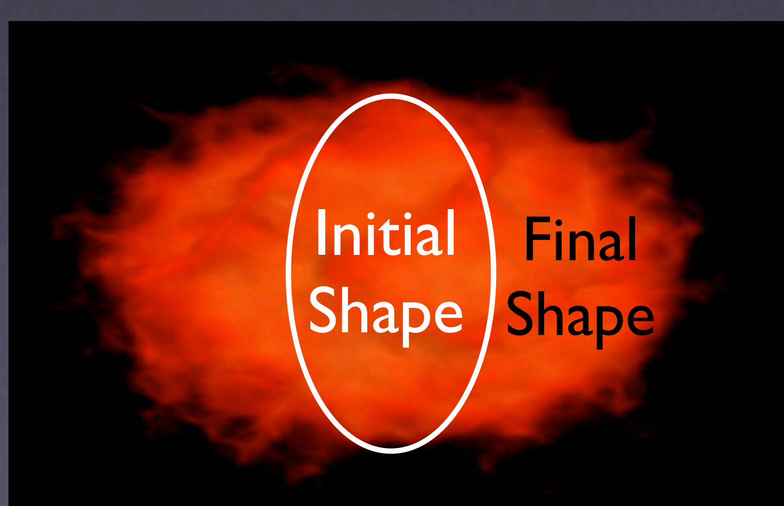


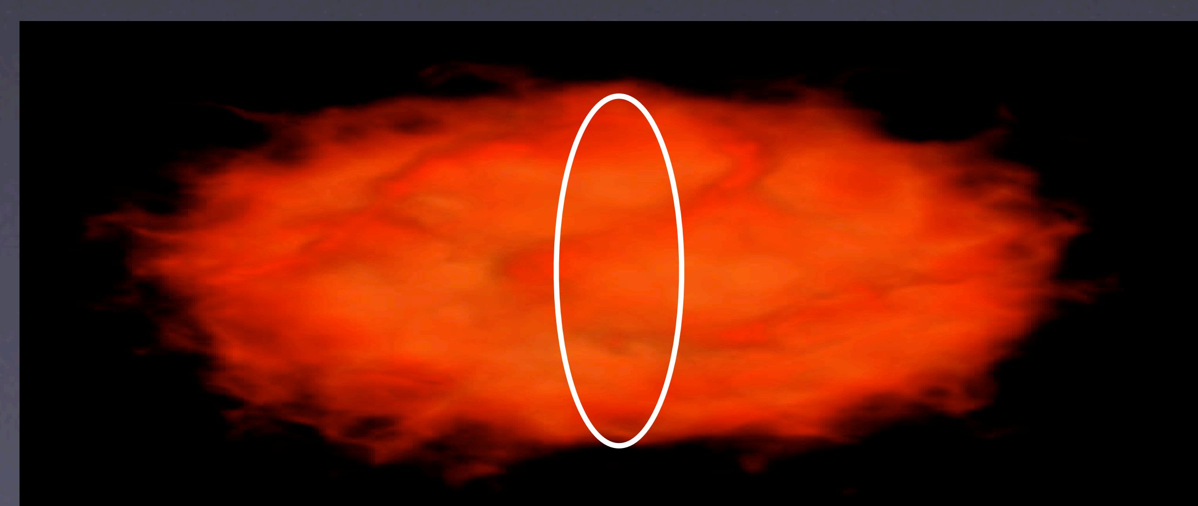


$$\sigma_y^2 = \ln\left(\frac{E_{NN}}{2M_P}\right)$$



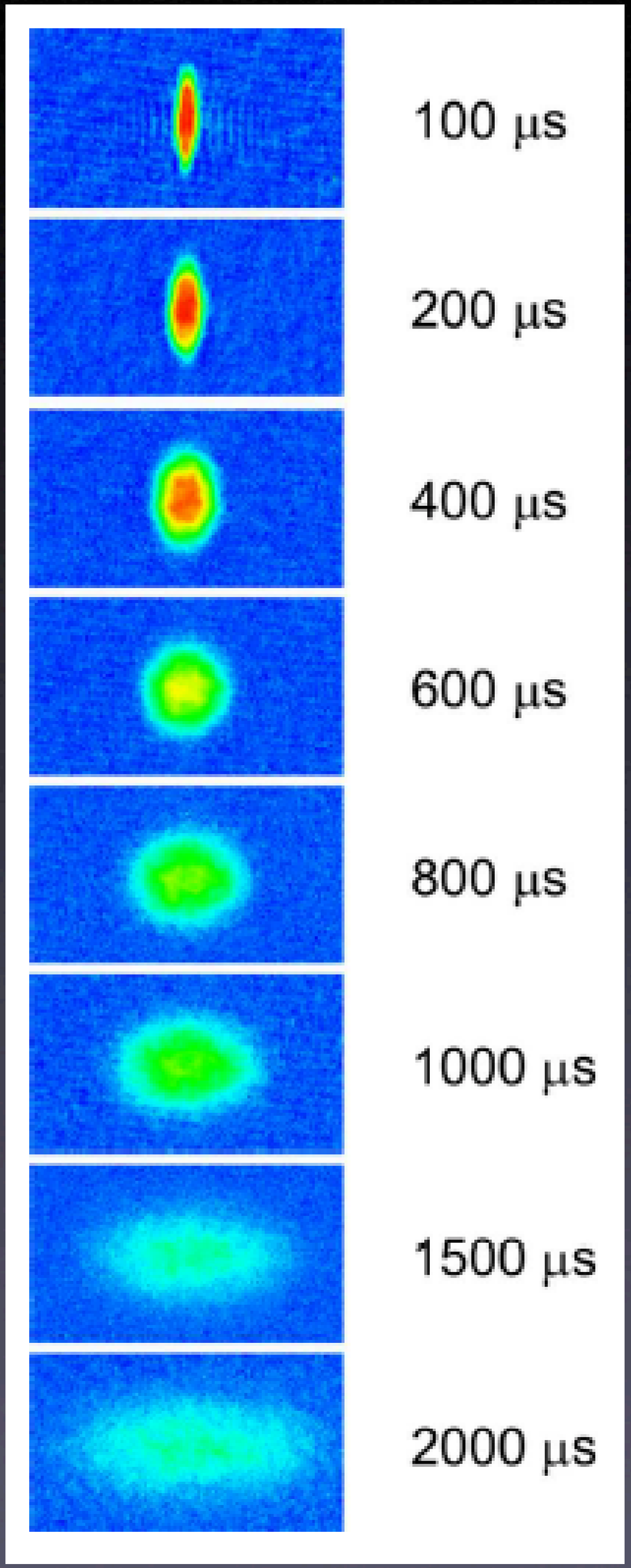
1955: Landau solves "Relativistic Hydrodynamics"





The more you squeeze it, the faster it explodes!

Unique to RHIC?

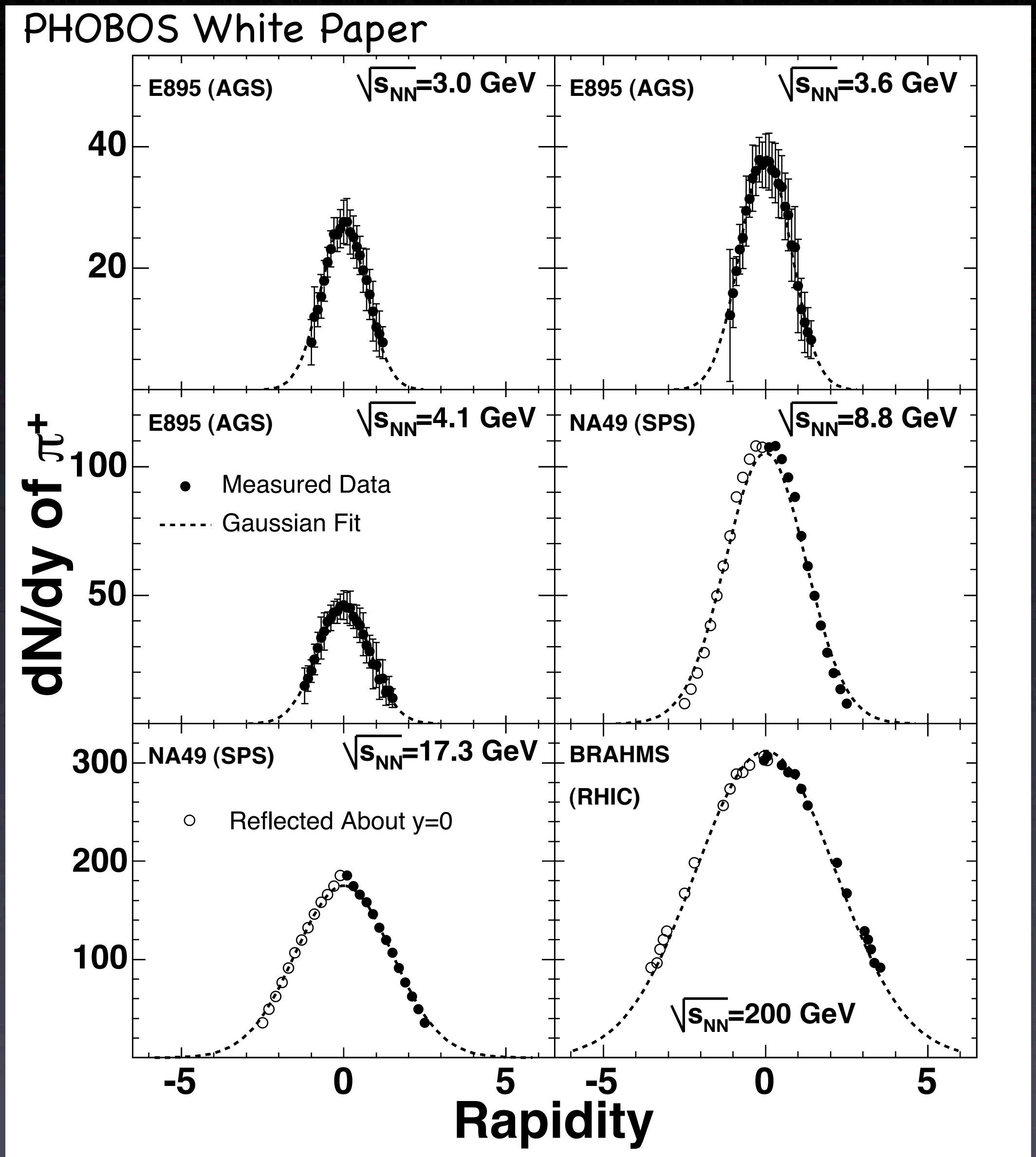


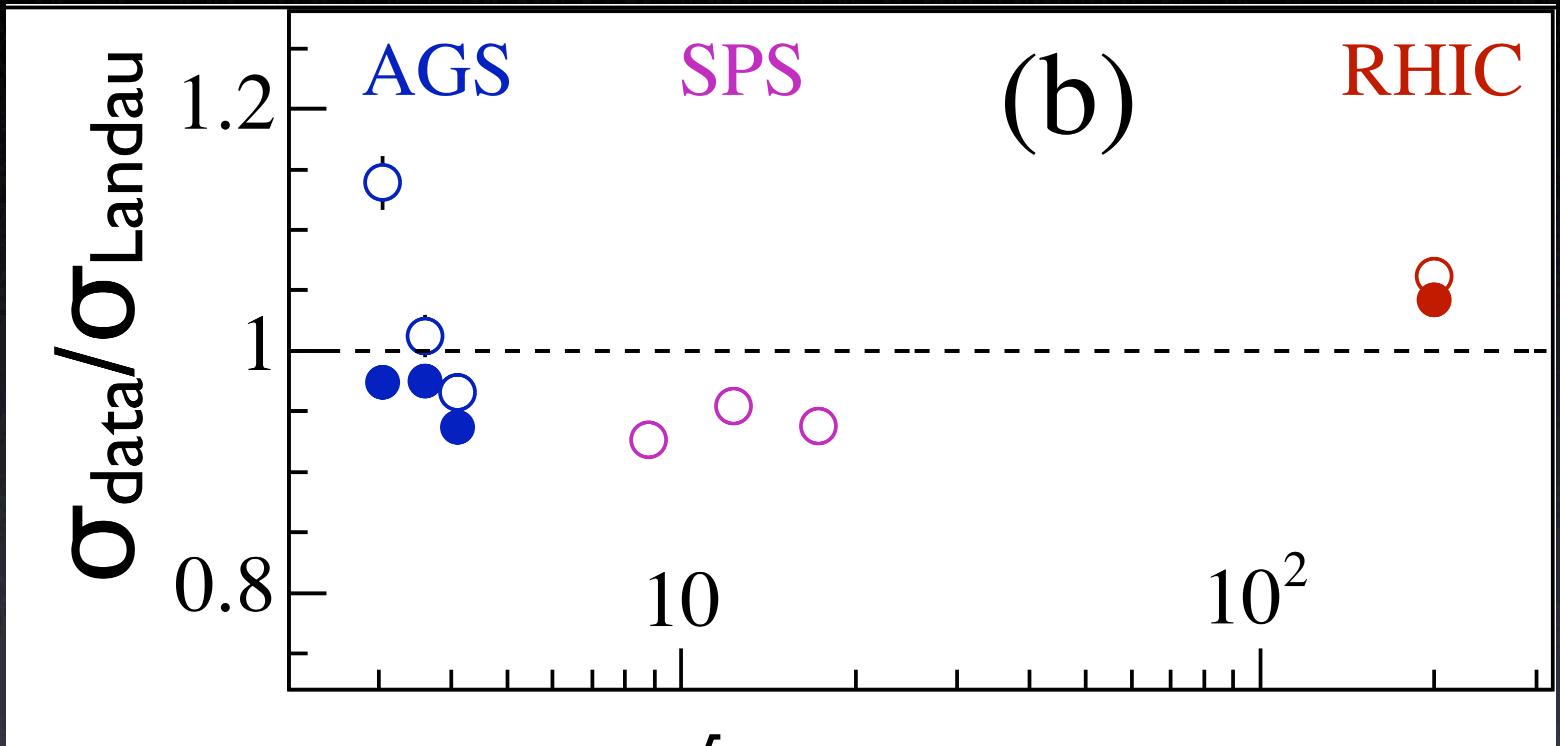
Strongly-coupled ^6Li atoms in a magnetic trap at the Feshbach resonance (O'Hara et al, 2003)

Any system with sufficiently-strong interactions will show "hydrodynamic" behavior

Ultracold atoms show it.
Do ultrahot RHIC collisions?

Landau Model vs. Data



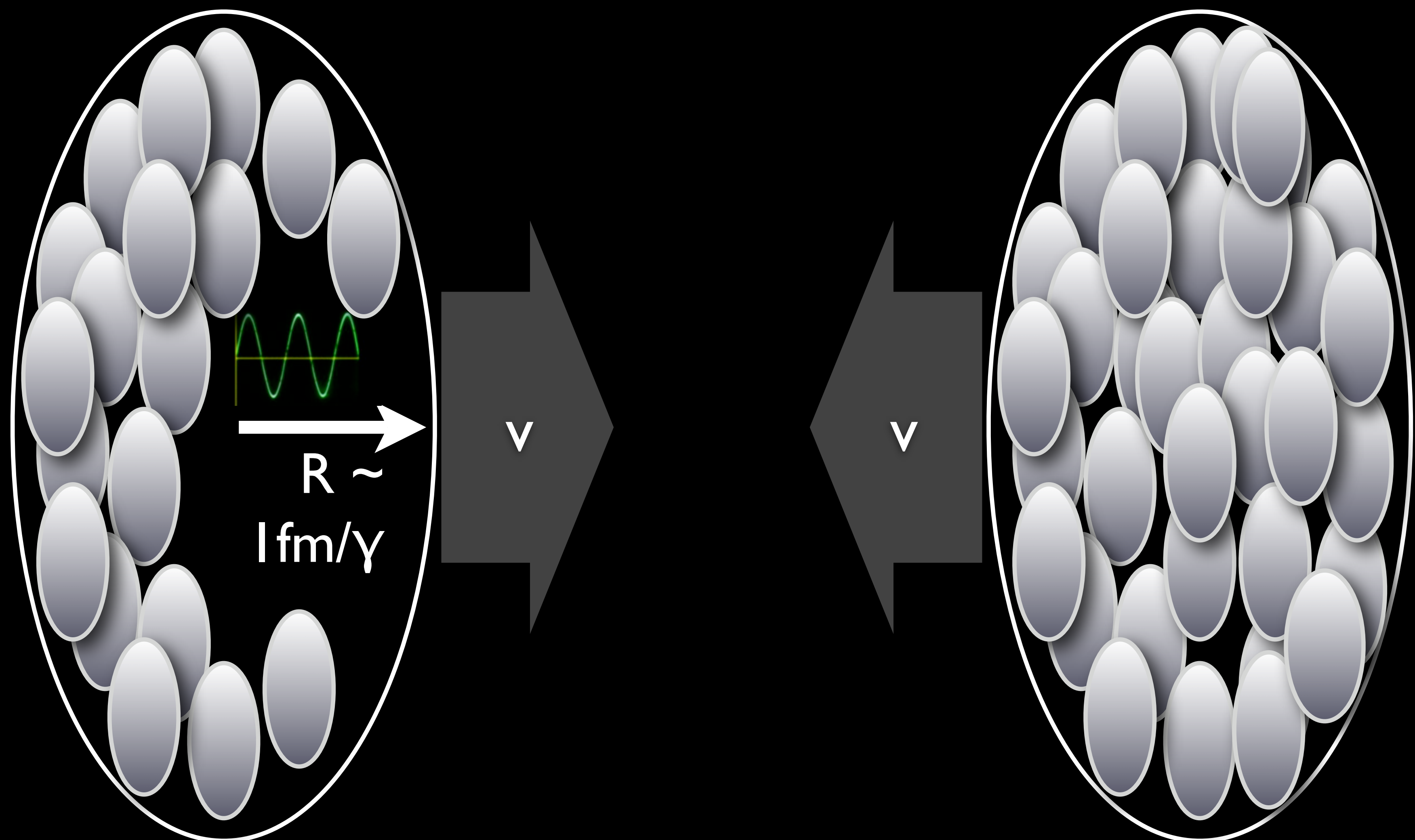


$$\sigma_y^2 = \ln\left(\frac{E_{NN}}{2M_P}\right)$$

Landau's predictions from 1955 remain valid in 2005

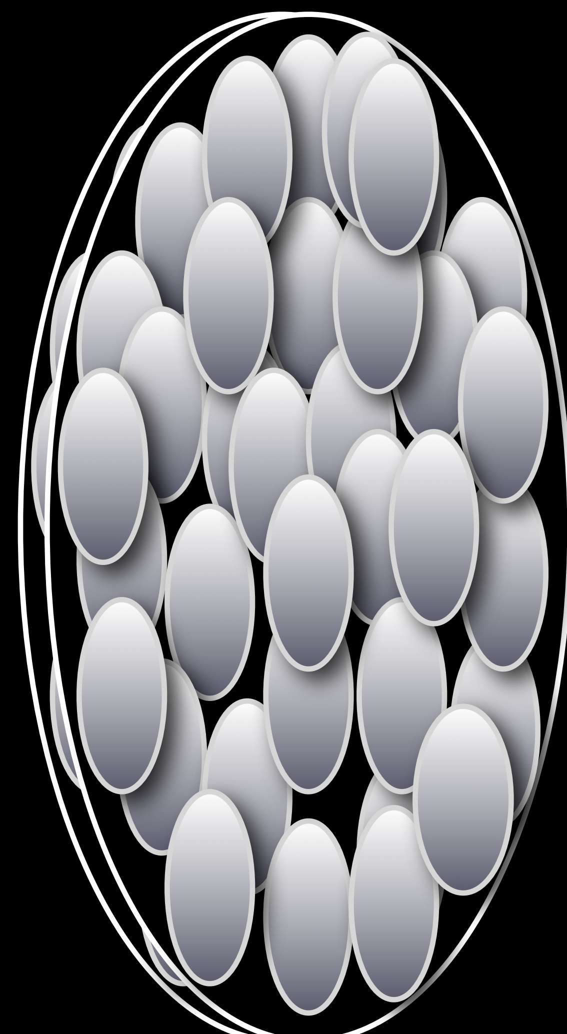
The longitudinal explosion in heavy ion collisions acts like a rapidly-thermalized fluid!

So What?



Try to imagine what is happening here:
Two nuclei racing towards each other at light speed...

So What?



They collide, and <u>something happens</u>...

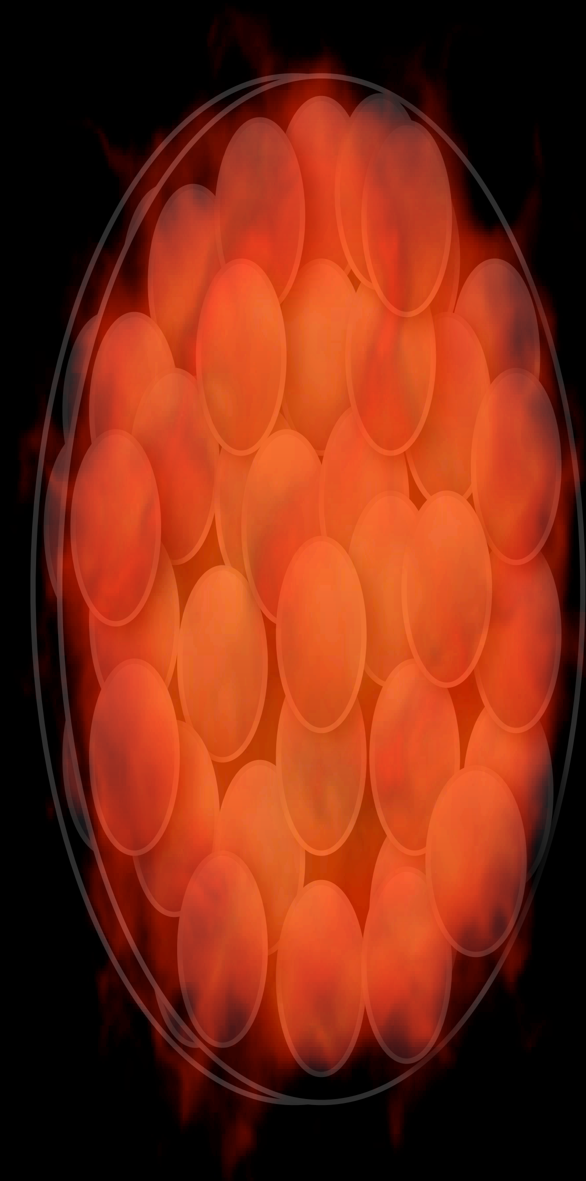
So What?

$t \sim 10^{-23}$ sec

$R \sim 10^{-15}$ m

$T > 2\times10^{12}$ °K

$\epsilon_0 \sim 3$ TeV/fm^3



Faster

Smaller

Hotter

Denser

...than anything you can imagine!

Something which makes the <u>fastest</u>, <u>smallest</u>, <u>hottest</u>, and most <u>dense</u> liquid created since the Big Bang!

What Makes RHIC Tick?

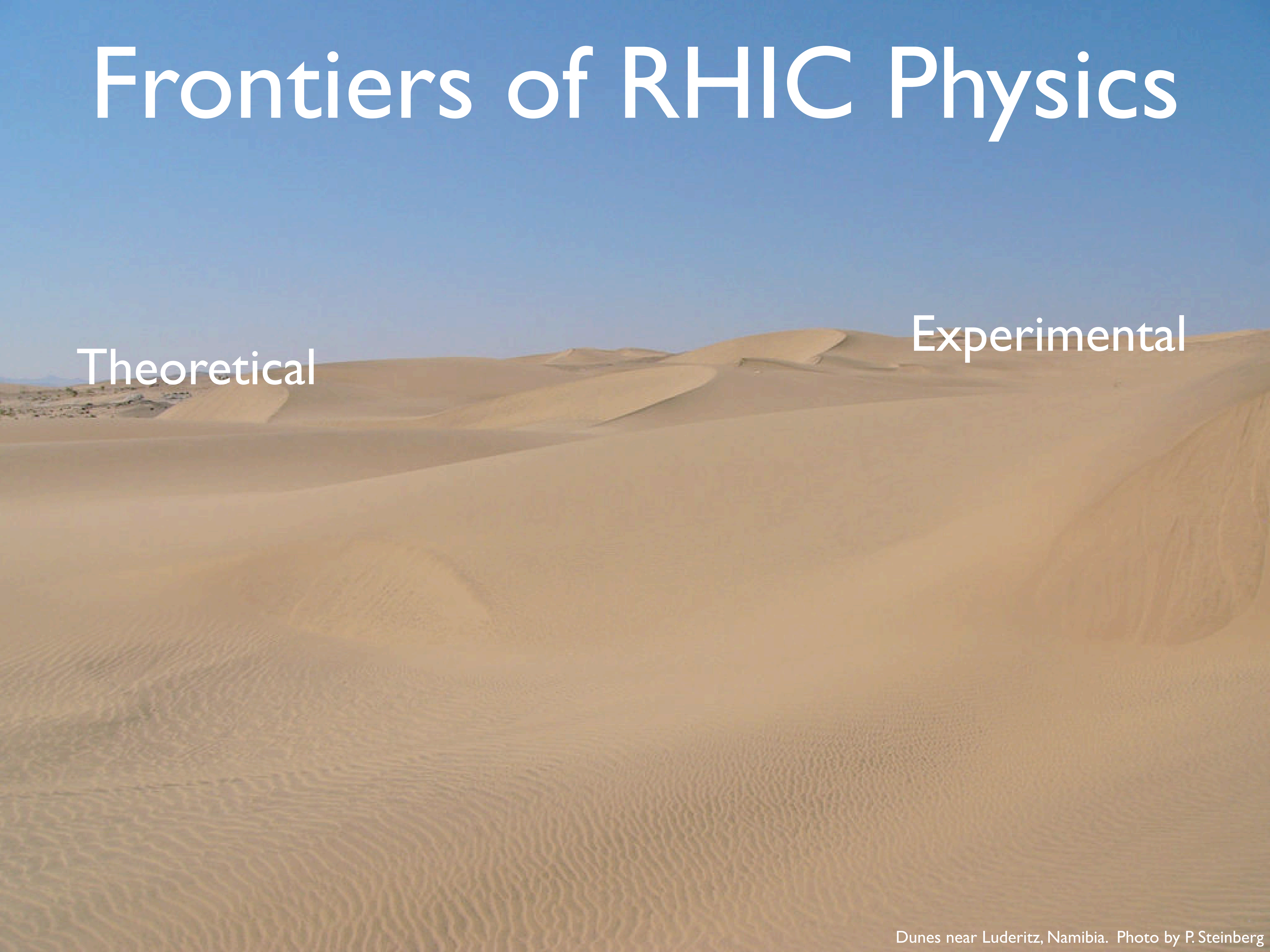
We can see that the matter created at RHIC forms quickly and is strongly interacting

But to be honest, we still don't know exactly *which* degrees of freedom are interacting

Expected a "gas" of quarks and gluons, but models based on these interactions do not have sufficient coupling strength to allow a good description of the data

Strongly Coupled QGP!

Frontiers of RHIC Physics



Dunes near Luderitz, Namibia. Photo by P. Steinberg

Black Holes at RHIC?

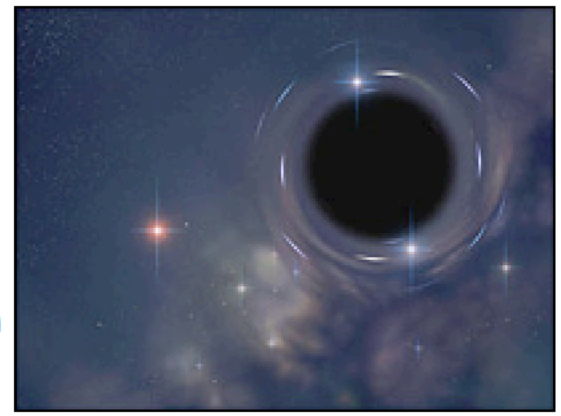
BBC NEWS UK EDITION

Last Updated: Thursday, 17 March, 2005, 11:30 GMT

E-mail this to a friend   Printable version

Lab fireball 'may be black hole'

A fireball created in a US particle accelerator has the characteristics of a black hole, a physicist has said.



Creating the conditions for the formation of black holes is one of the aims of particle physics

It was generated at the Relativistic Heavy Ion Collider (RHIC) in New York, US, which smashes beams of gold nuclei together at near light speeds.

Horatiu Nastase says his calculations show that the core of the fireball has a striking similarity to a black hole.

His work has been published on the pre-print website arxiv.org and is reported in New Scientist magazine.

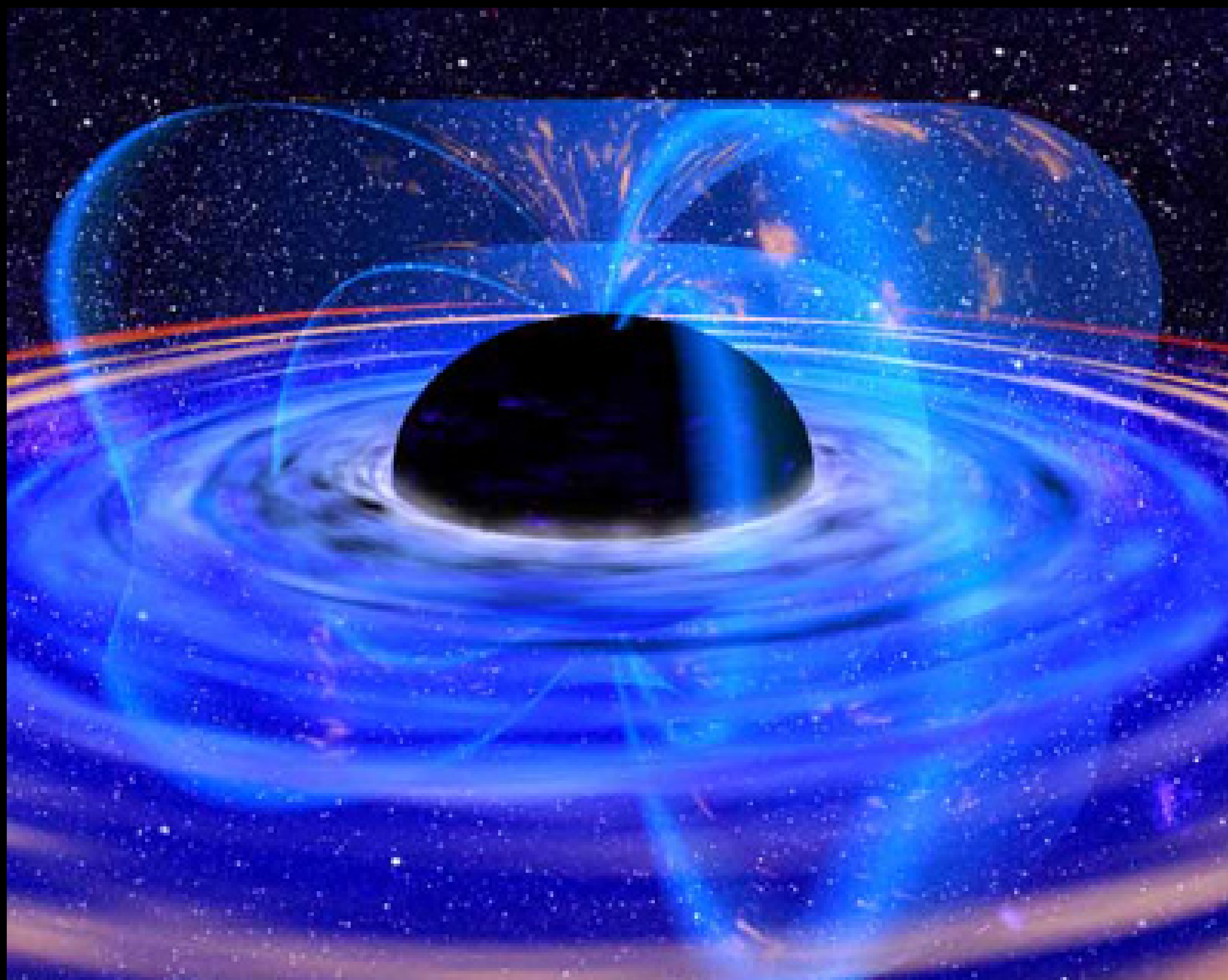
When the gold nuclei smash into each other they are broken down into particles called quarks and gluons.

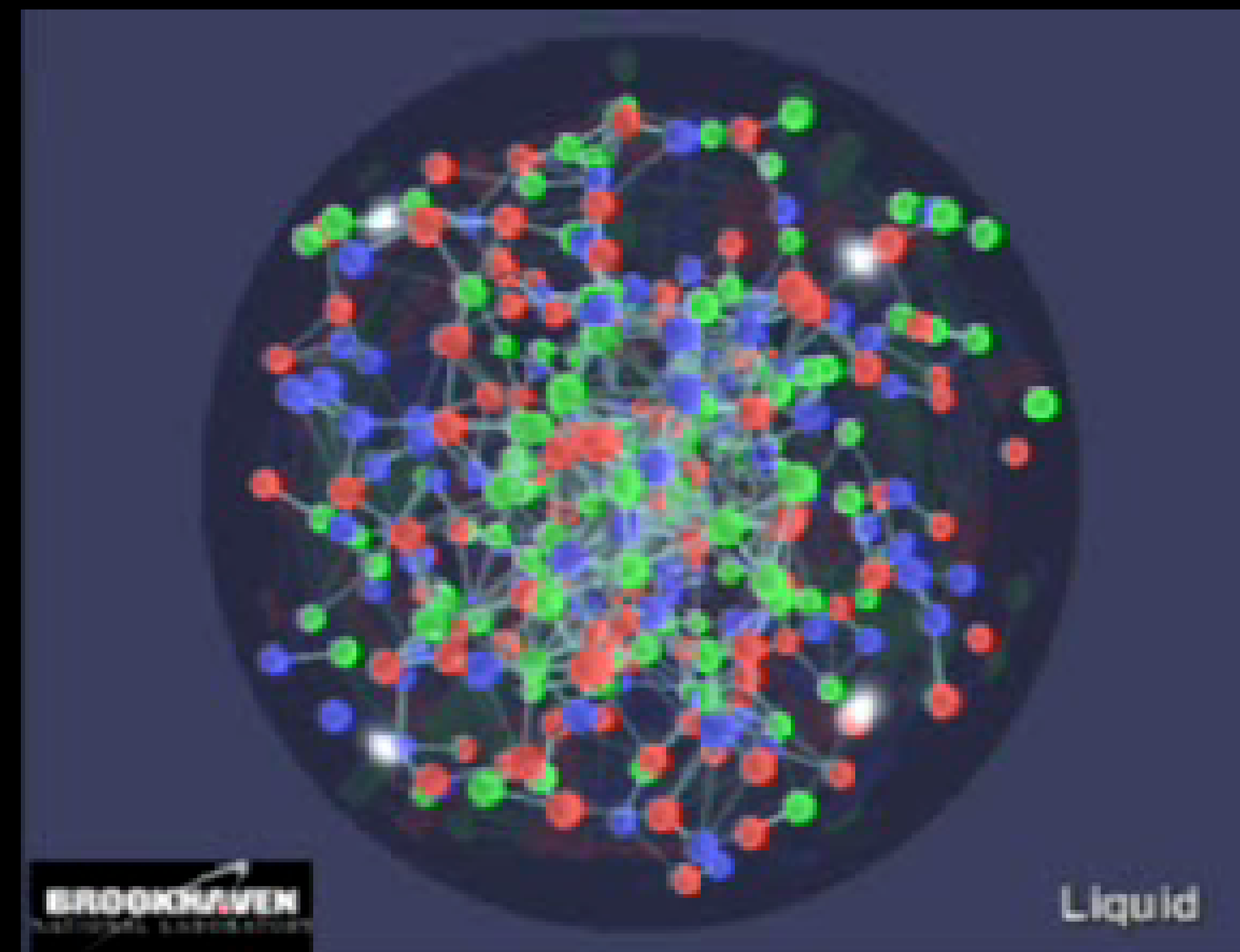
These form a ball of plasma about 300 times hotter than the surface of the Sun. This fireball, which lasts just 10 million, billion, billionths of a second, can be detected because it absorbs jets of particles produced by the beam collisions.

But Nastase, of Brown University in Providence, Rhode Island, says there is something unusual about it.

sorry, no...

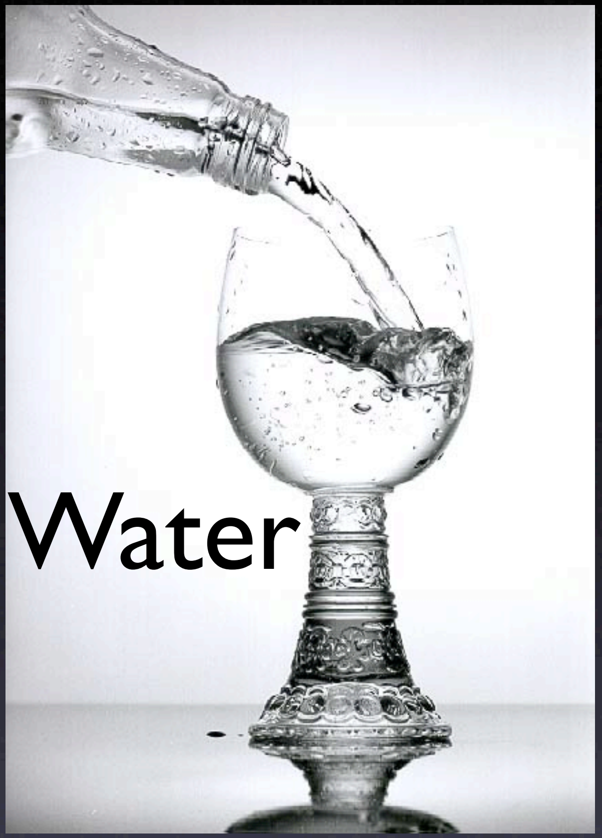
A Mathematical Connection

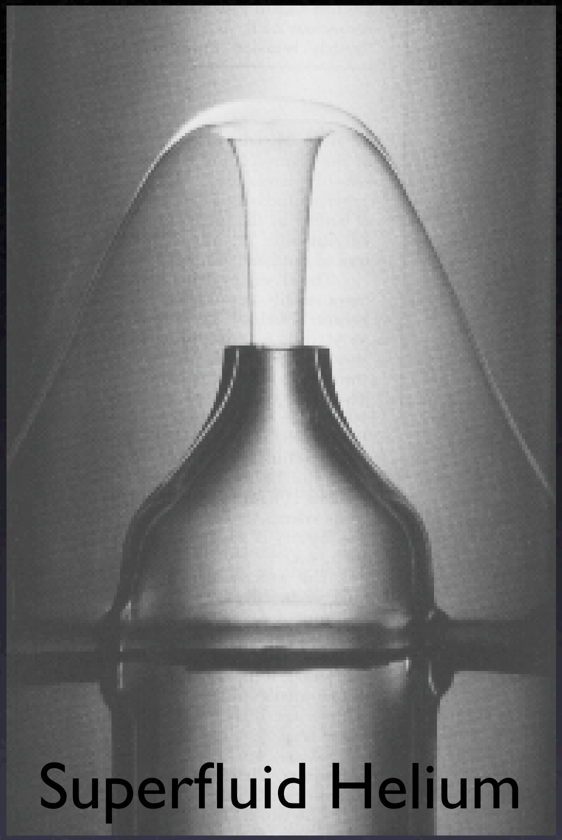




10-dimensional Black Hole (not a “real” black hole...) ⟷ “Quark-Gluon Liquid”?

Keyword: Viscosity





Some liquids like to “flow” more than other liquids.

“Viscous” fluids (e.g. honey or motor oil) don’t like to flow

A perfect fluid (no viscosity) only likes to flow!

PRL **94,** 111601 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

sQGP String Theory!

Viscosity in ~~Strongly Interacting Quantum Field Theories~~ from ~~Black Hole Physics~~

P. K. Kovtun,[1] D. T. Son,[2] and A. O. Starinets[3]

[1]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
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[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

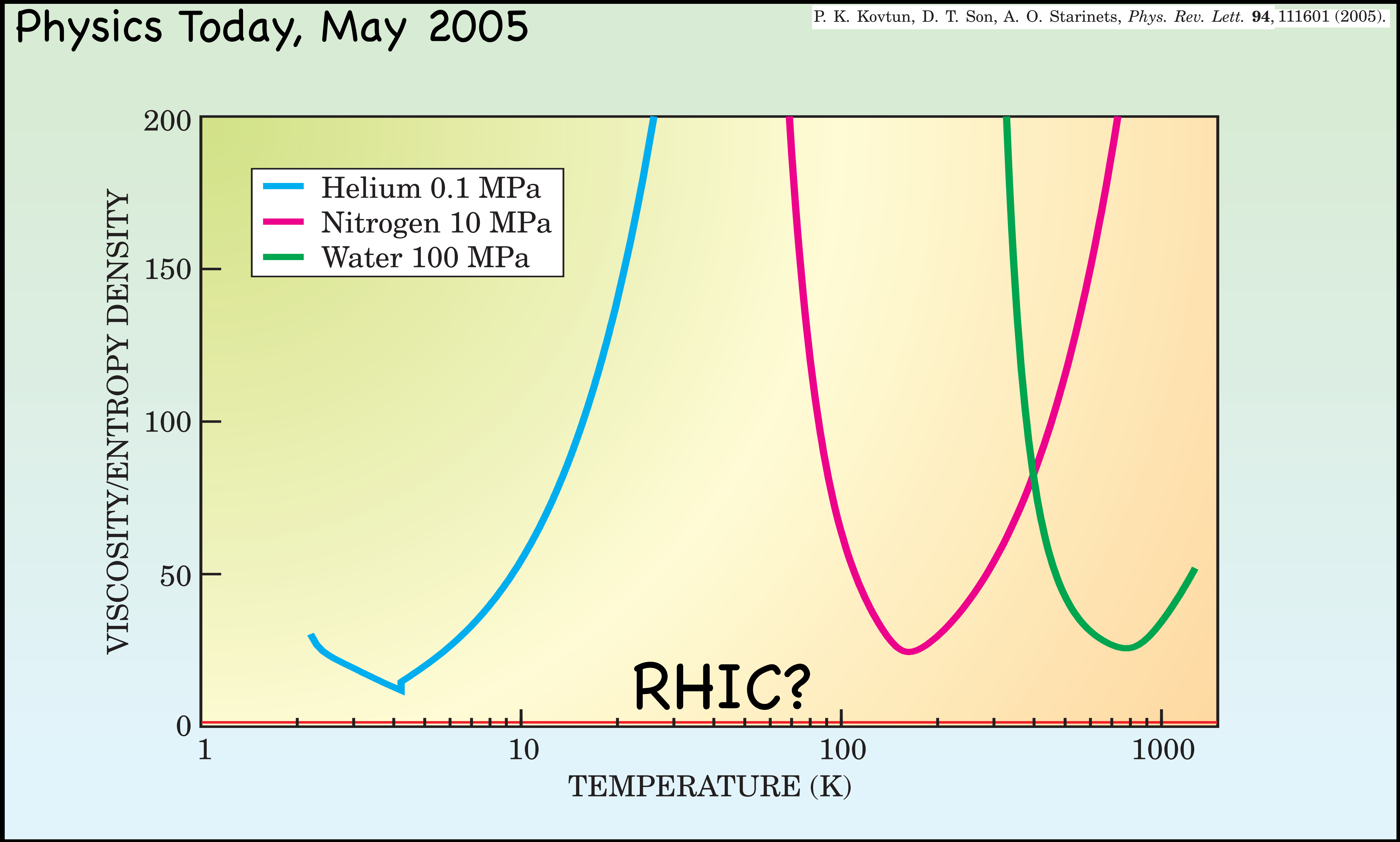
(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti–de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.

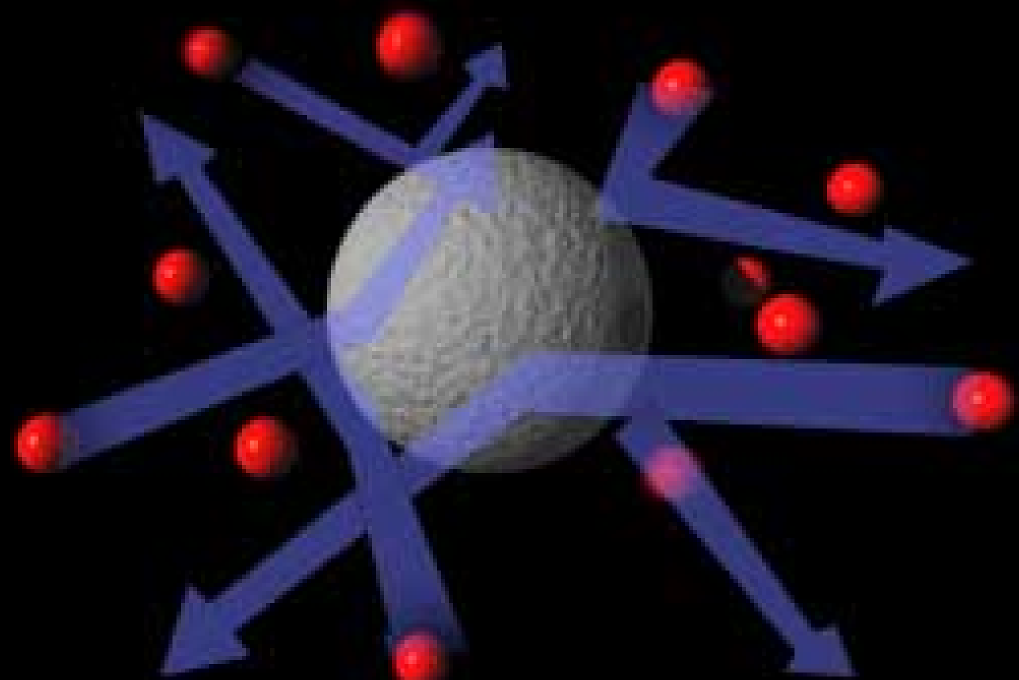
DOI: 10.1103/PhysRevLett.94.111601 PACS numbers: 11.10.Wx, 04.70.Dy, 11.25.Tq, 47.75.+f

Details aside, this paper makes a calculation about RHIC physics using a 10 dimensional black hole and gets a meaningful result about its viscosity...

Lower Viscosity Bound



A perfect liquid is impossible - but is RHIC the most perfect?



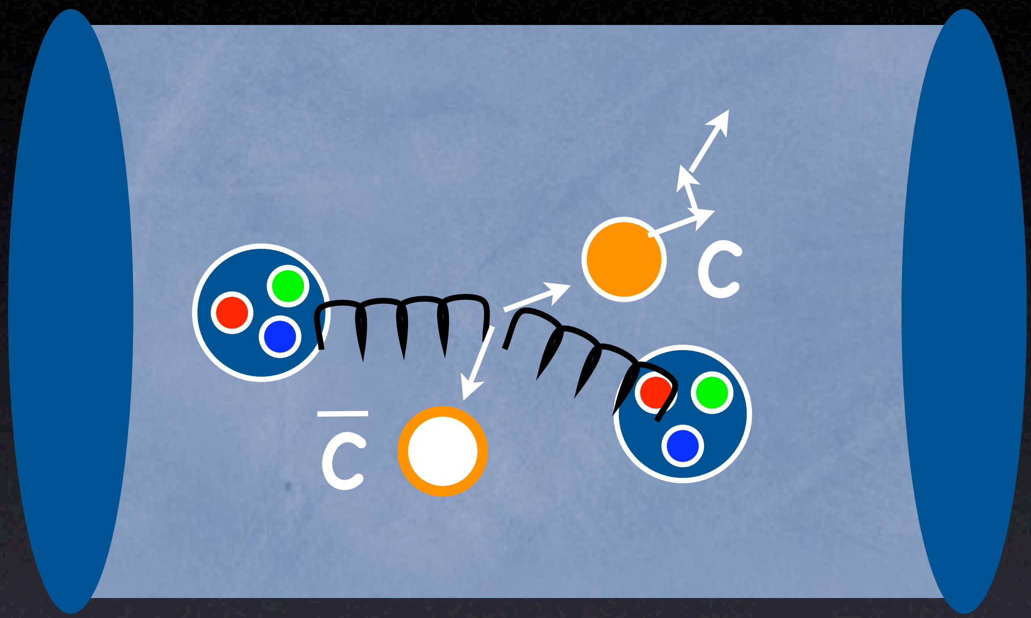
Viscosity is intimately connected to Brownian motion (1905!)

Can measure viscosity by measuring diffusion

How do we study such processes in a sQGP?...

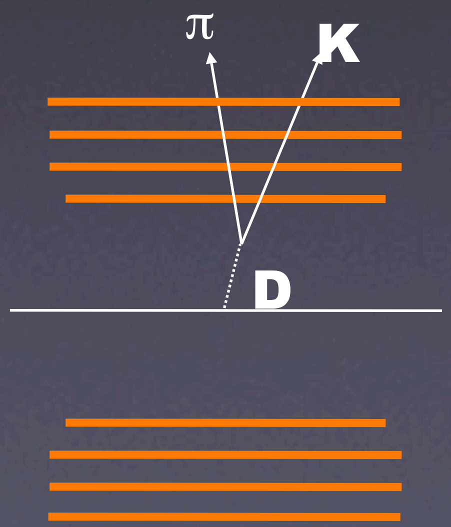
$$D = \frac{3kT}{\alpha}. \qquad \alpha = 6\pi\eta a$$

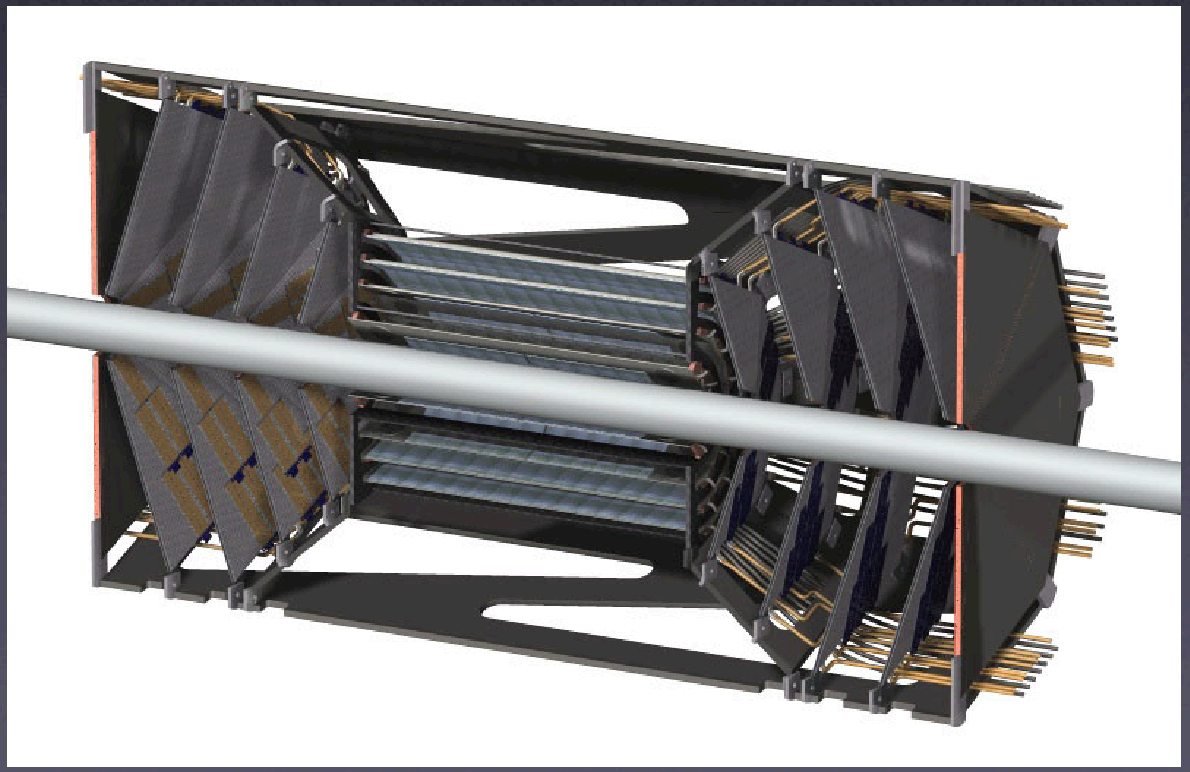
Heavy Flavor @ RHIC II



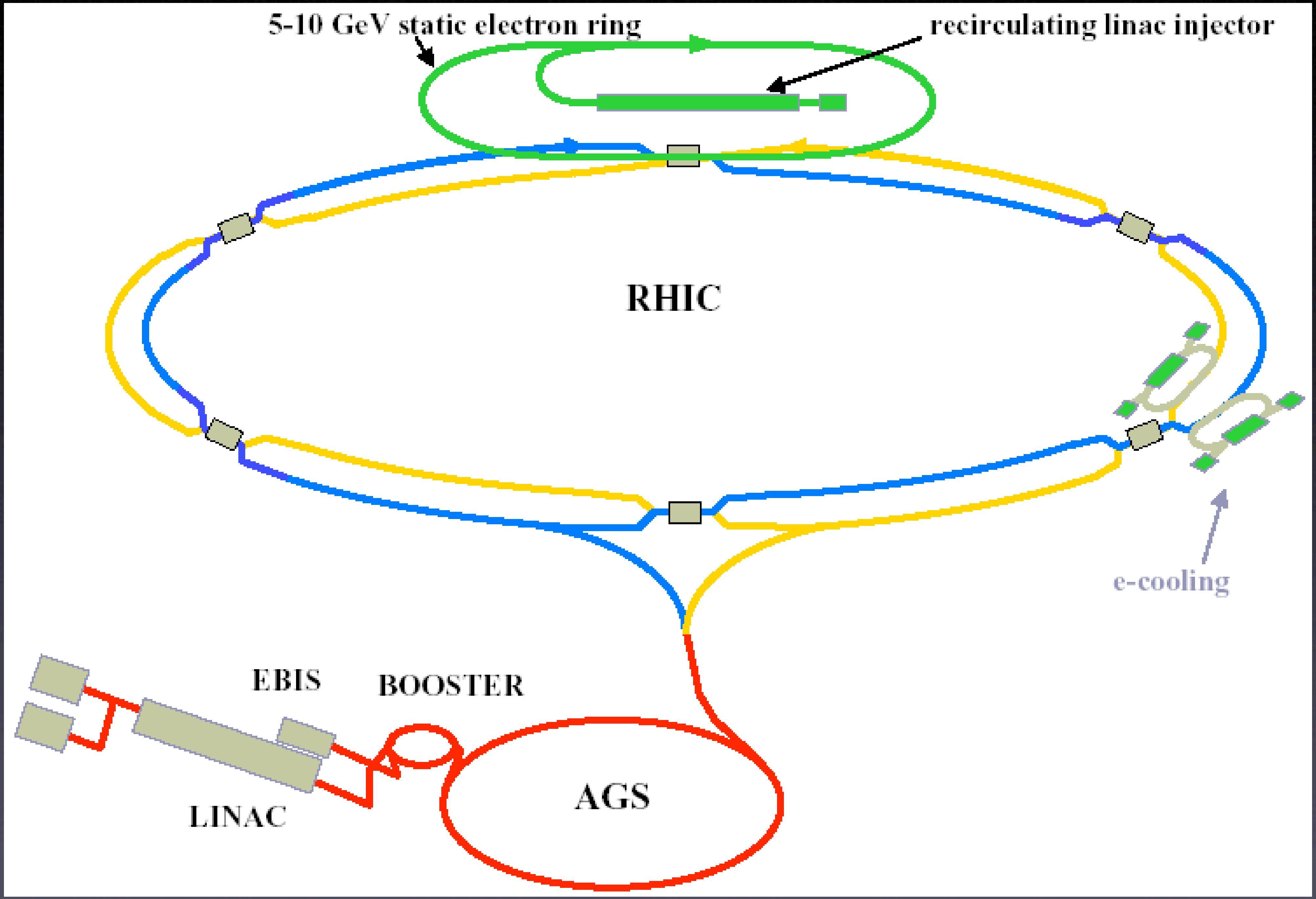
To probe the transport properties of the system, would be useful to study thermalization of heavier objects → e.g. heavy quarks

New silicon detectors being developed for PHENIX & STAR to measure charmed particles by means of displaced decay vertices



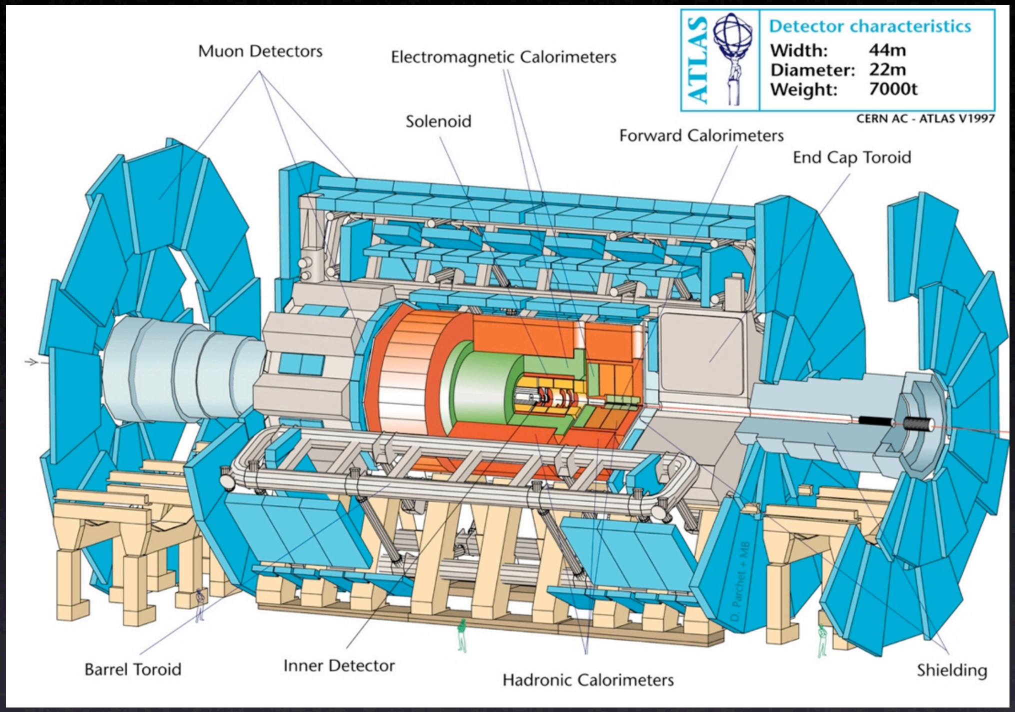


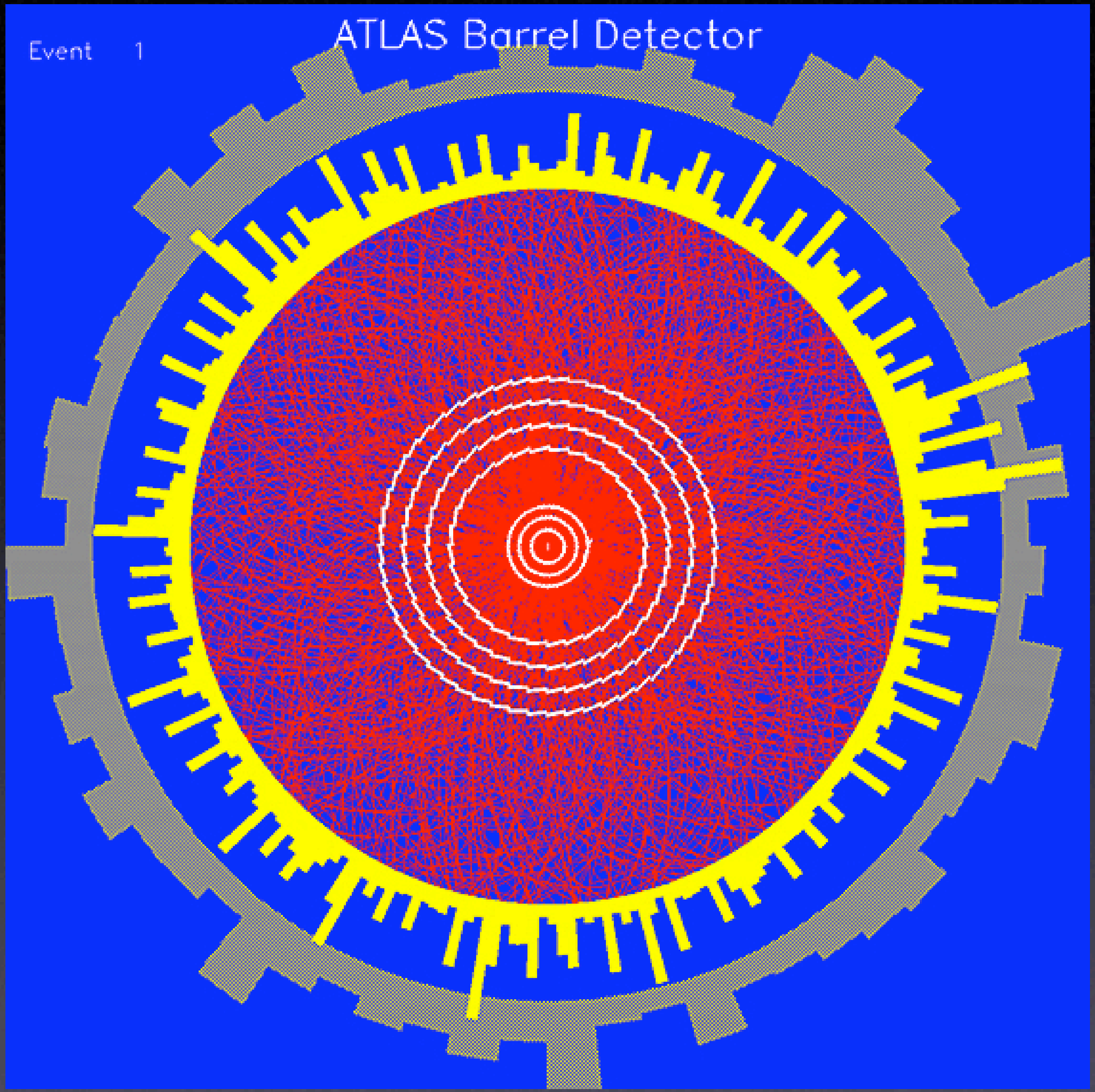
QCDLab (RHIC II)



10x the luminosity (event rate) of RHIC for gold-gold collisions!

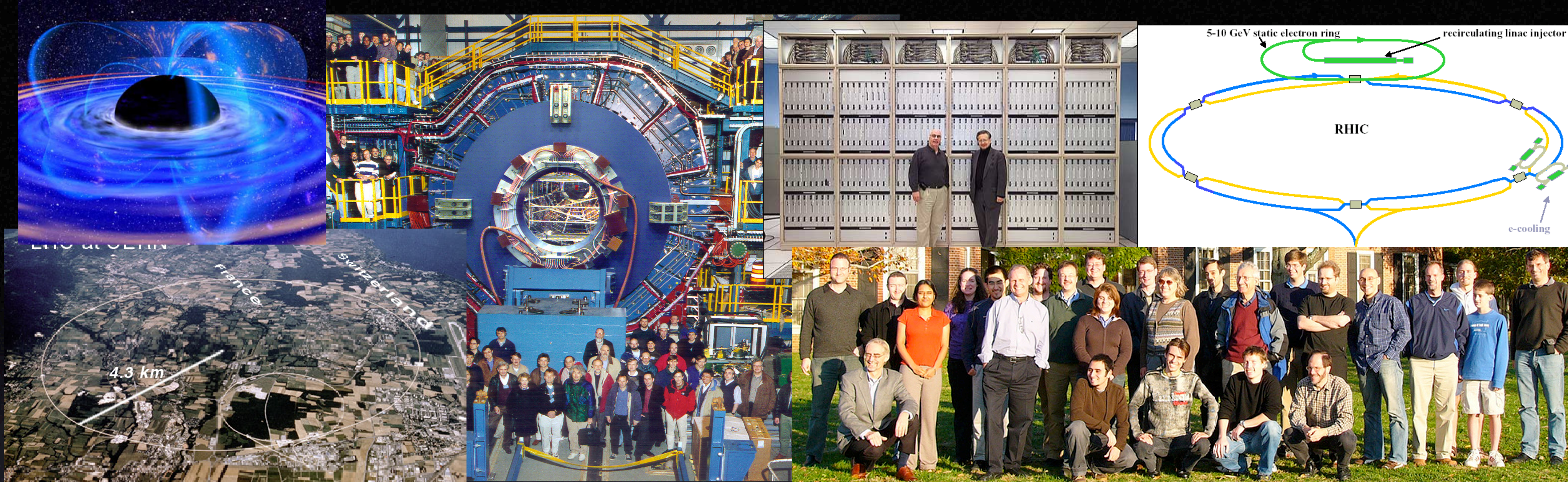
The Future: Ions @ LHC





High energies (x2250 contraction), huge multiplicities!
will the trends discussed here break down?
Three experiments (ATLAS/CMS/ALICE) will study Pb+Pb!

Understanding the strong interaction has a long history



But we still have a lot of work to do!

Gell-Mann v. Steinberg

Born 1929
Yale, JE '48
PhD, MIT '51
Invented quarks

Born 1969
Yale, JE '92
PhD, MIT '98
Studies quarks